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(54) **HEAT-ASSISTED MAGNETIC RECORDING DEVICE INCORPORATING LASER HEATER FOR IMPROVED LASER STABILITY**

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Related U.S. Application Data

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(60) Provisional application No. 62/744,729, filed on Oct. 12, 2018.

(51) **Int. Cl.**
G11B 13/08 (2006.01)
G11B 5/00 (2006.01)

(52) **U.S. Cl.**
CPC ***G11B 13/08*** (2013.01); *G11B 2005/0021* (2013.01)

(58) **Field of Classification Search**
CPC G11B 11/1051; G11B 2005/0021; G11B 11/105; G11B 5/00; G11B 5/6088; G11B 11/10511; G11B 5/59633; G11B 5/59627; G11B 5/59655
USPC 360/59, 75, 313; 369/13.33, 13.32
See application file for complete search history.

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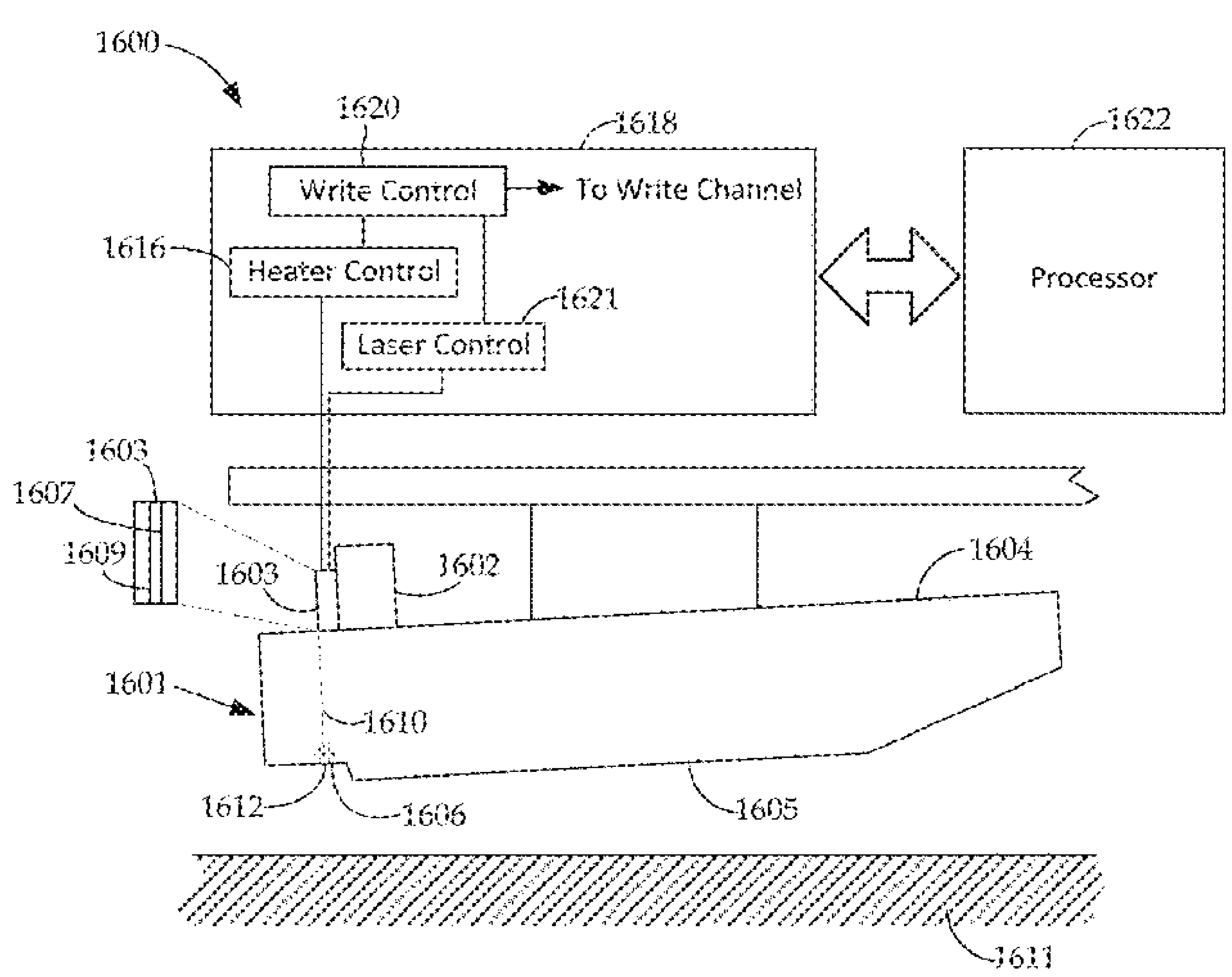
Primary Examiner — Nabil Z Hindi
(74) *Attorney, Agent, or Firm* — Mueting Raasch Group

(57) **ABSTRACT**

An apparatus comprises a slider configured to facilitate heat assisted magnetic recording and a submount affixed to the slider. A laser unit is affixed to the submount and comprises a laser operable in a non-lasing state and a lasing state. A heater is embedded in the laser unit or the submount. The heater is configured to generate preheat for heating the laser during the non-lasing state and to generate steering heat for heating the laser during the lasing state.

18 Claims, 13 Drawing Sheets



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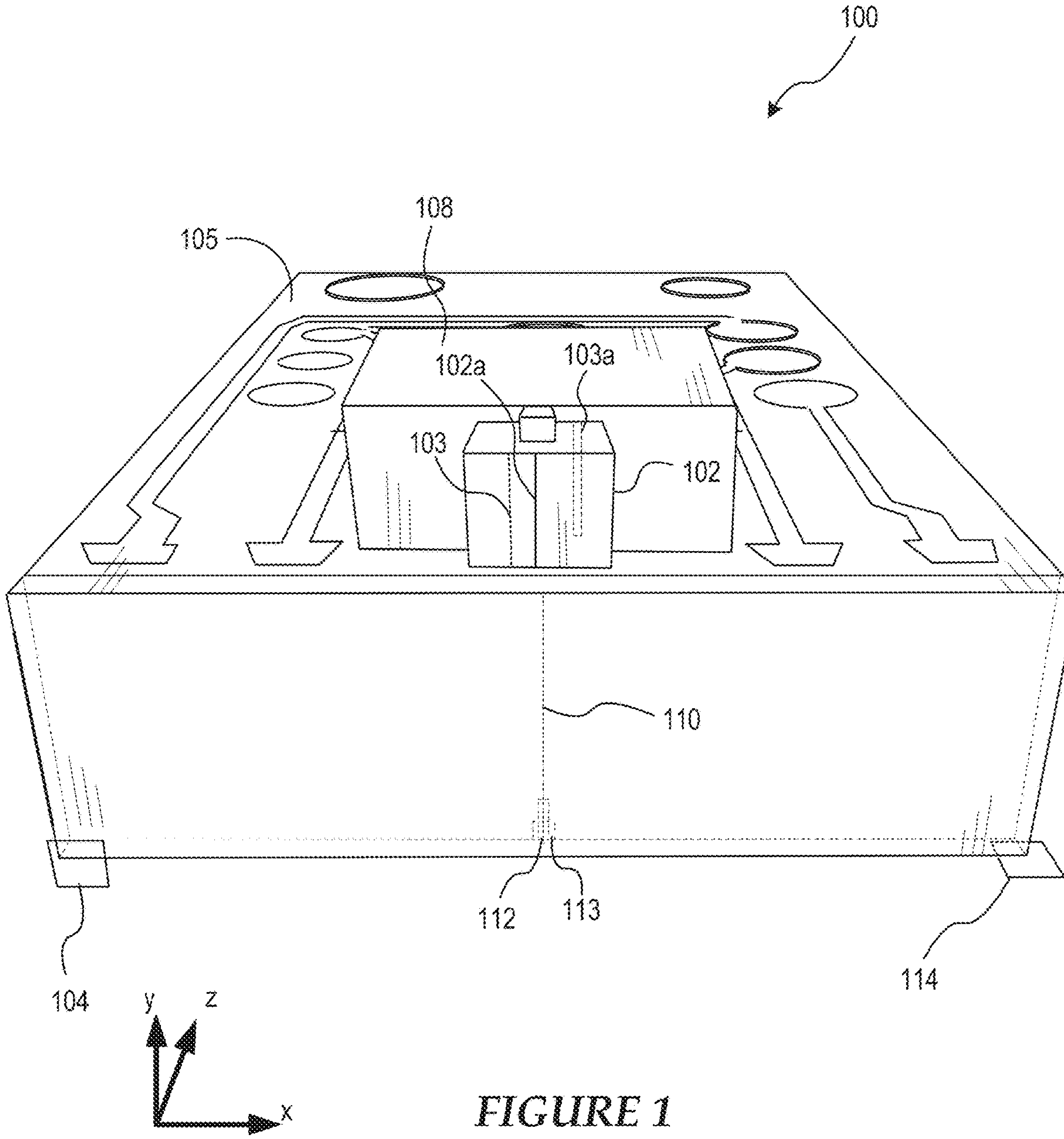


FIGURE 1

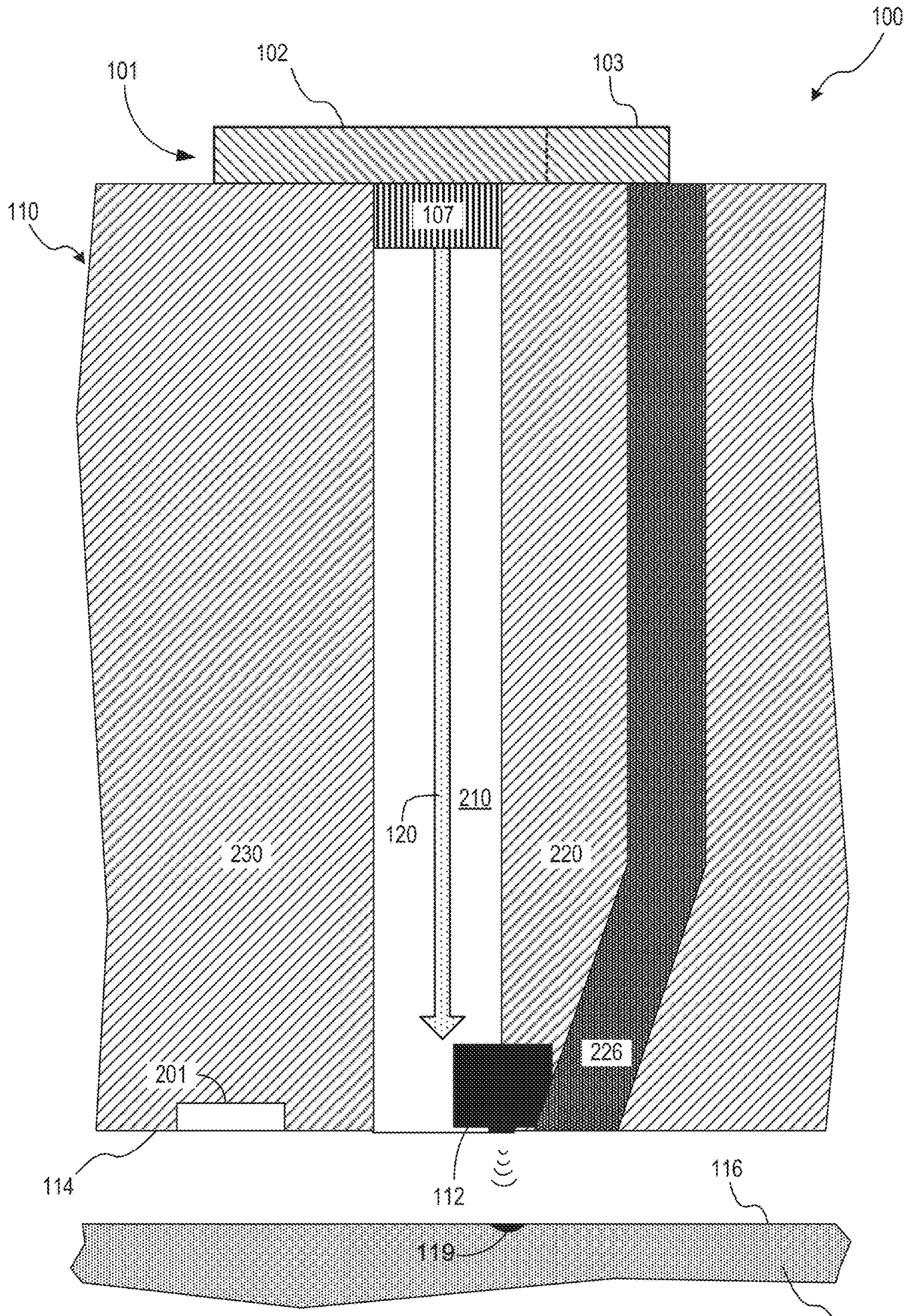
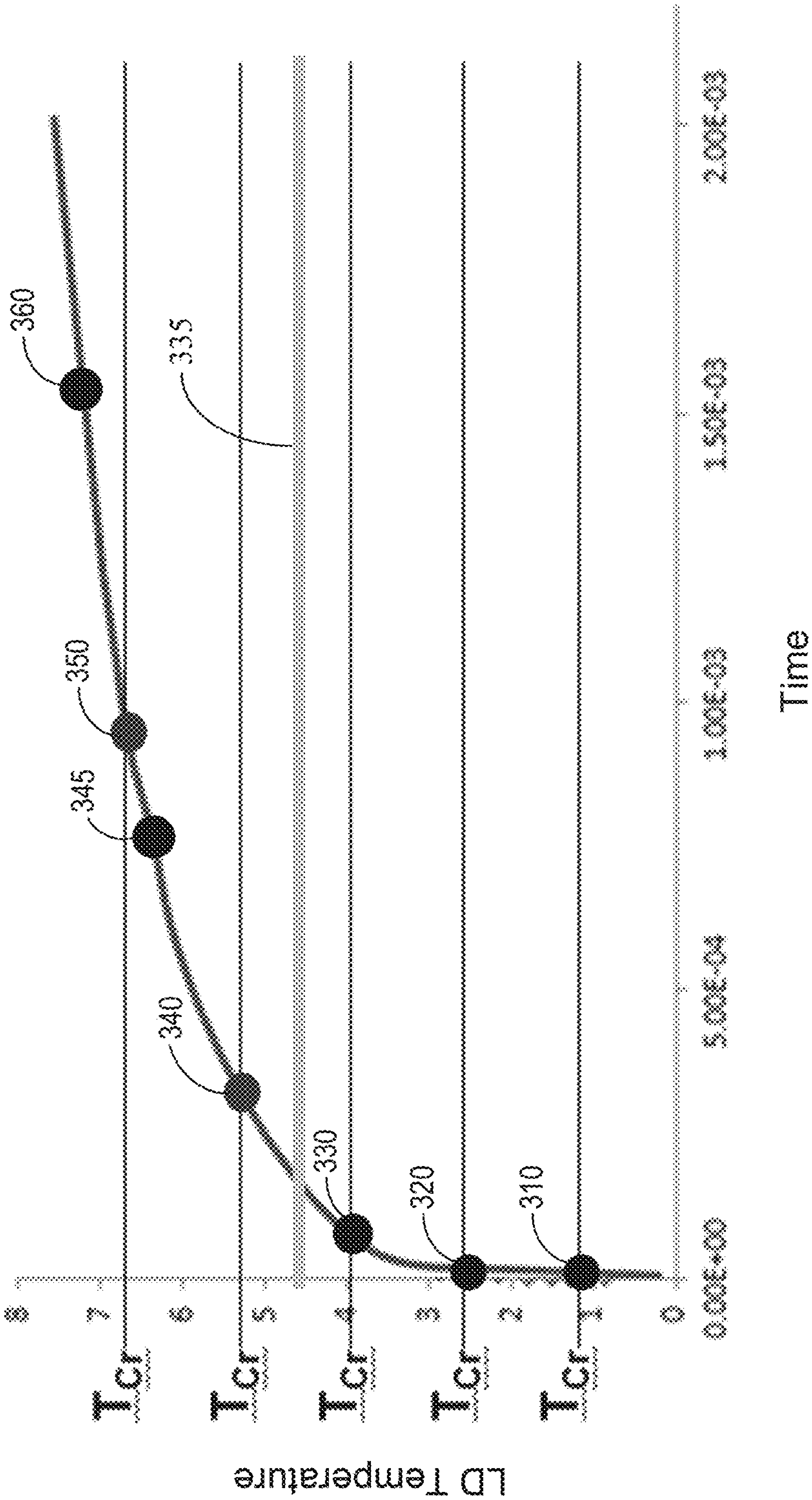

100
101
102
103
110
107
210
120
230
220
226
201
114
112
116
119
118

FIGURE 2

FIGURE 3


LD Temperature
Time
0
1
2
3
4
5
6
7
8
0.00E+00
5.00E-04
1.00E-03
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310
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335
340
345
350
360

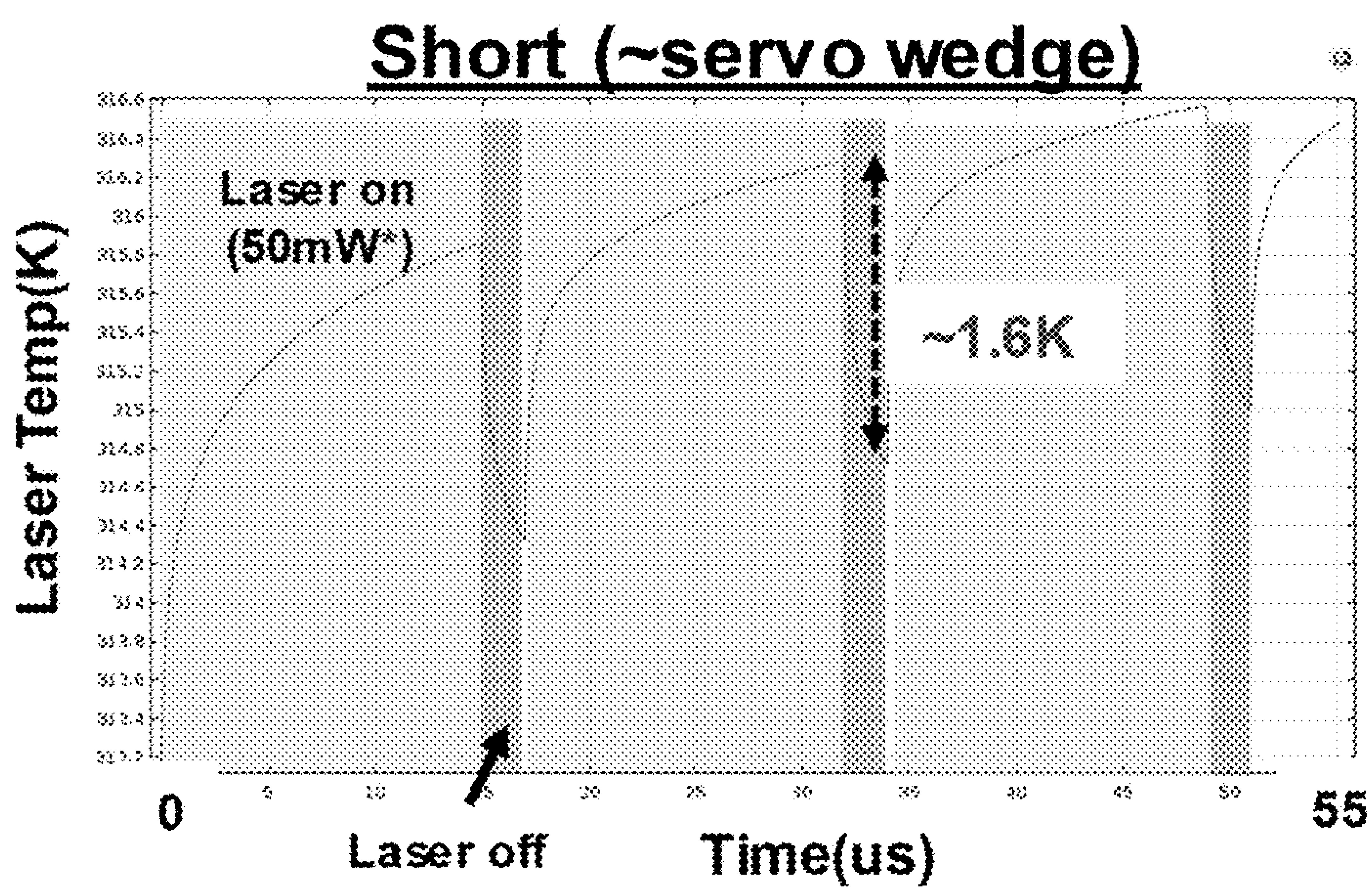


FIGURE 4

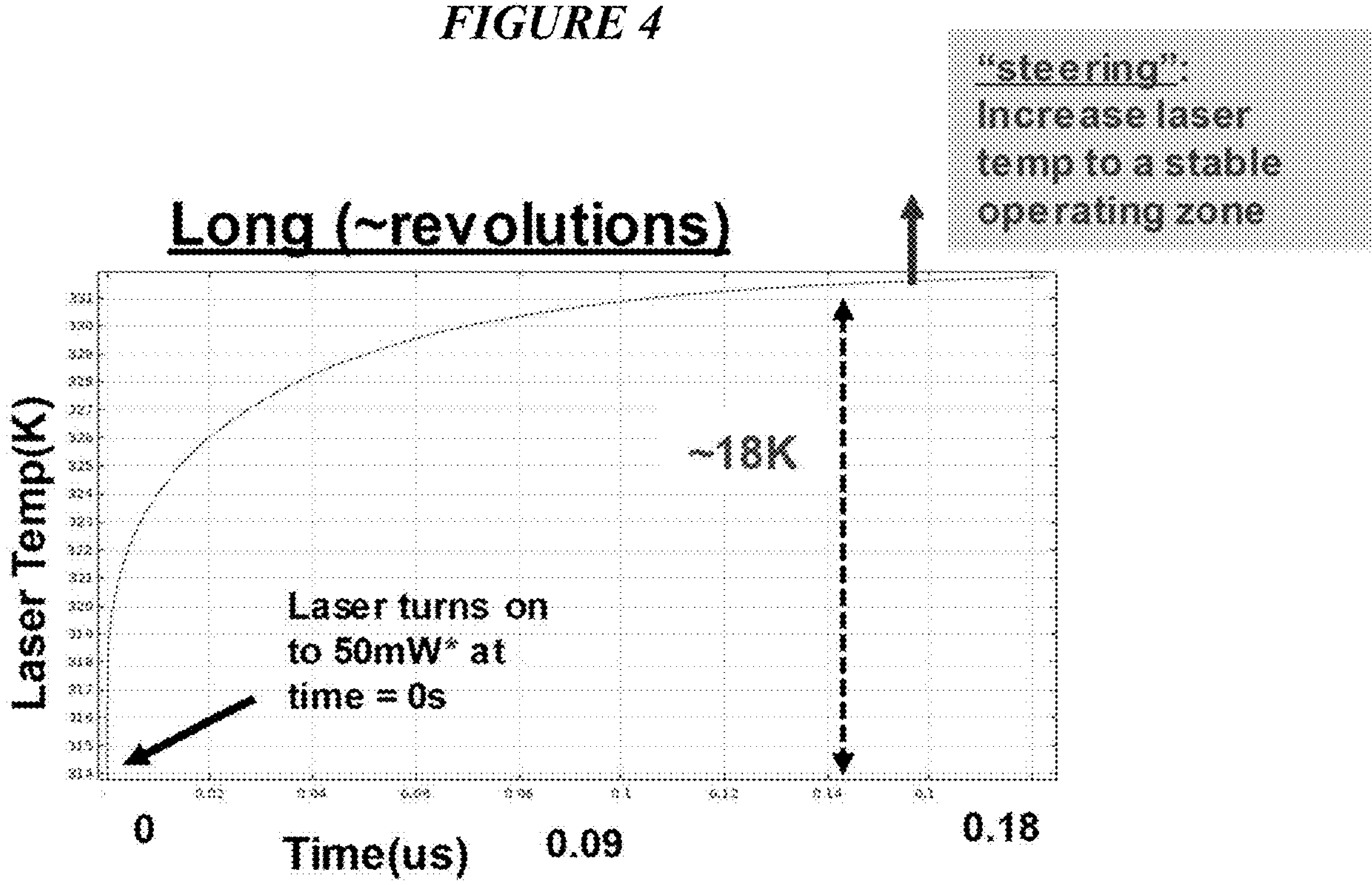


FIGURE 5

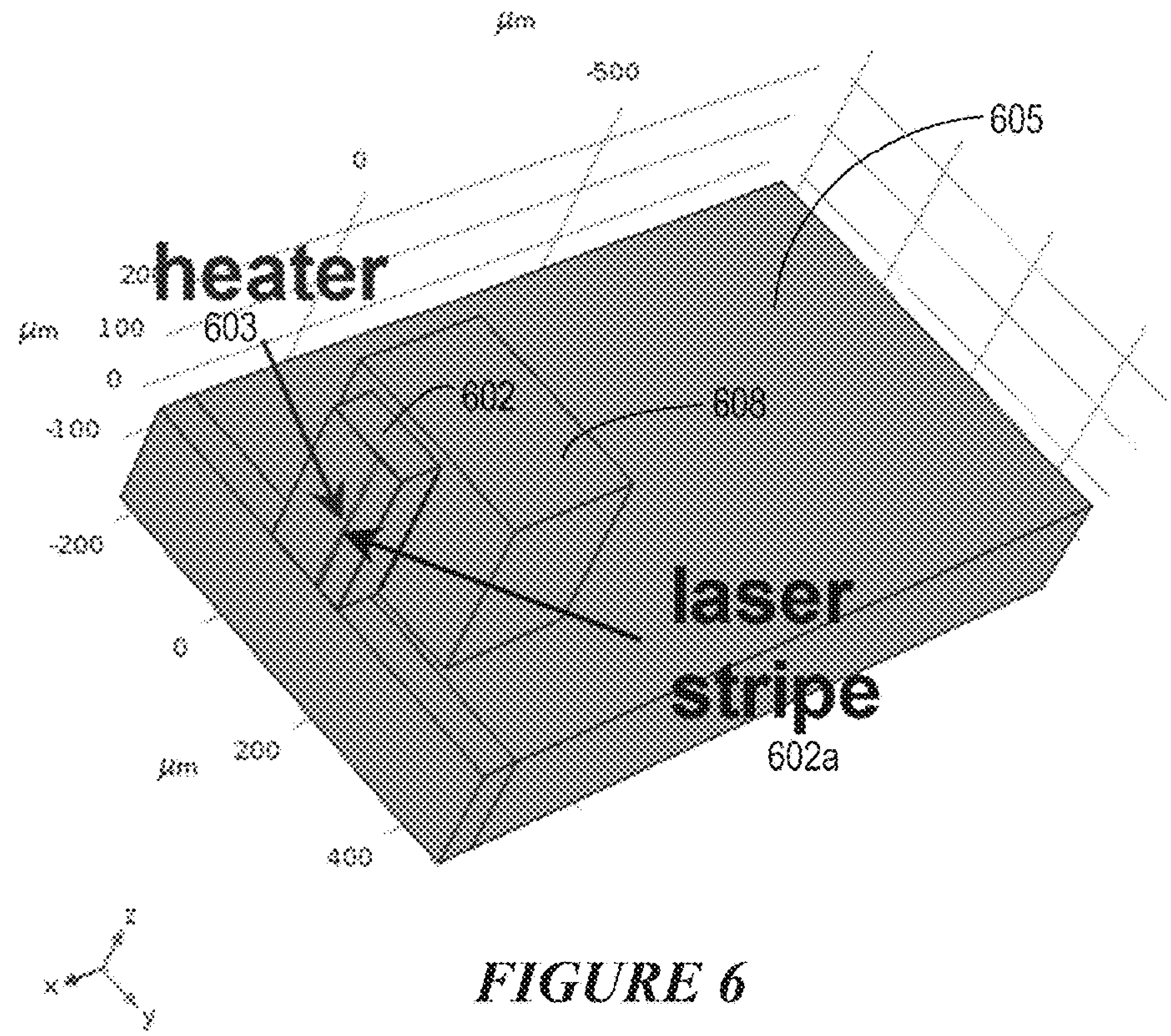


FIGURE 6

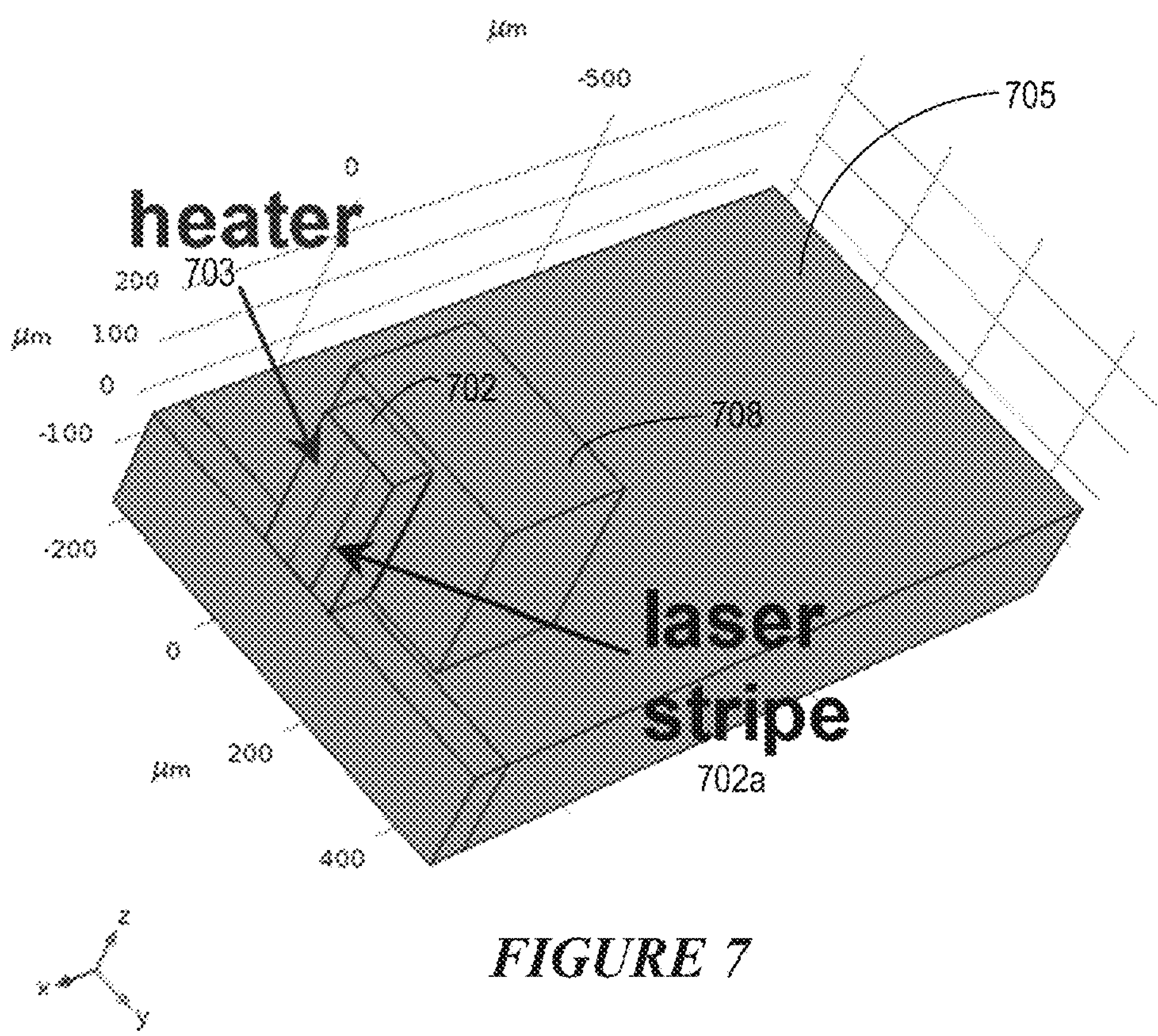
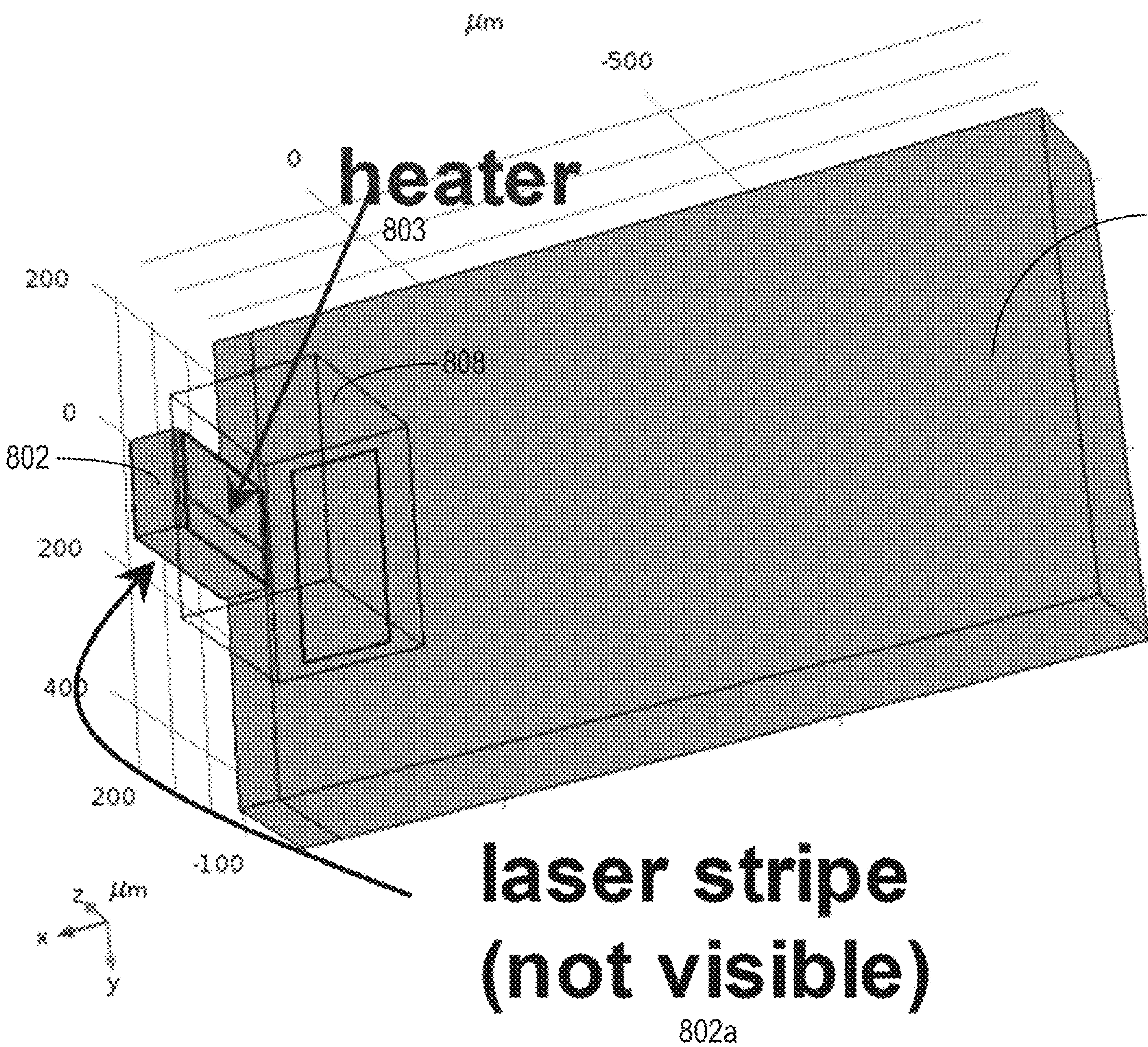


FIGURE 7

FIGURE 8



μm
-500
0
heater
803
805
200
808
0
802
200
400
200
-100
z
μm
x
y
laser stripe
(not visible)
802a

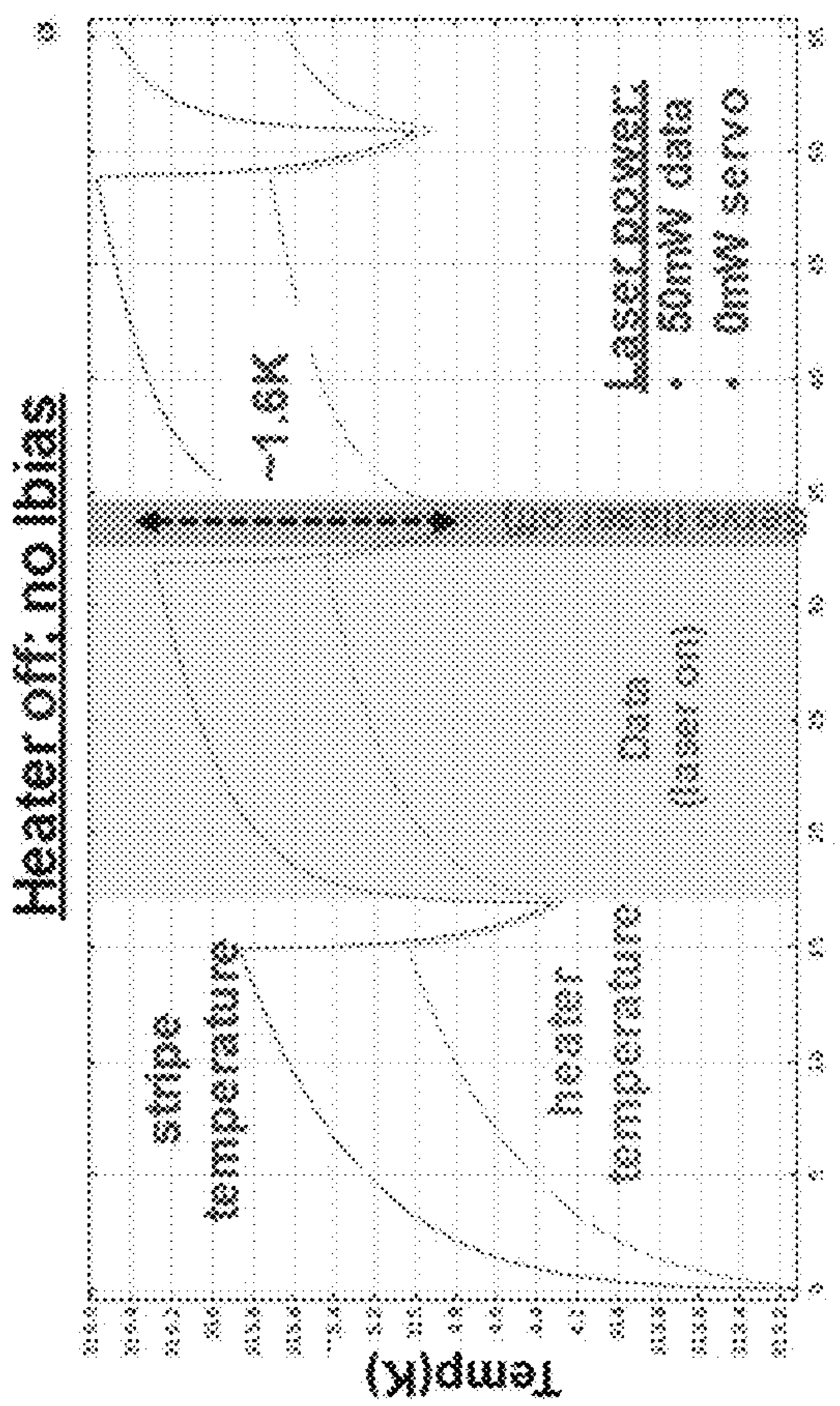


FIGURE 9

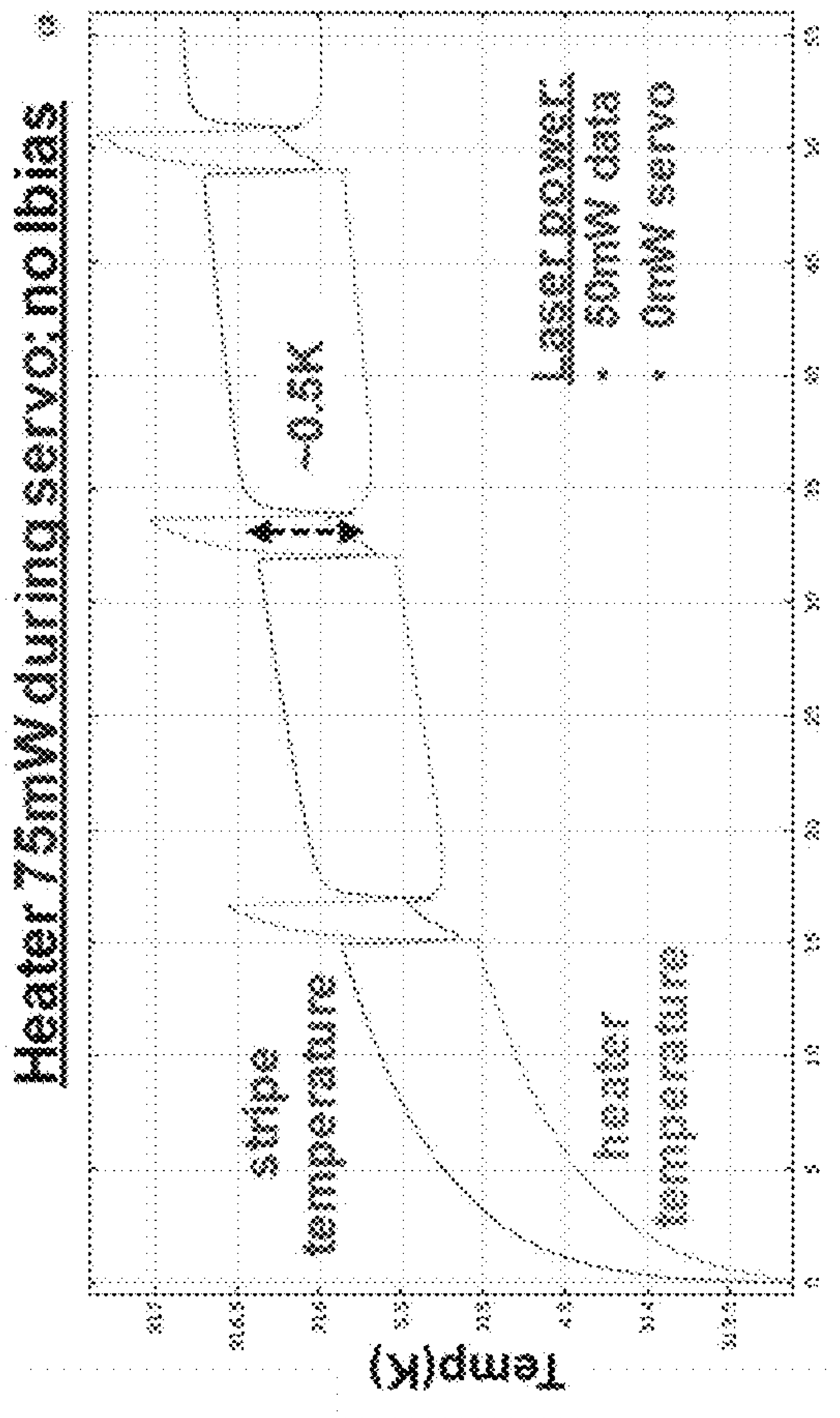


FIGURE 10

FIGURE 11A

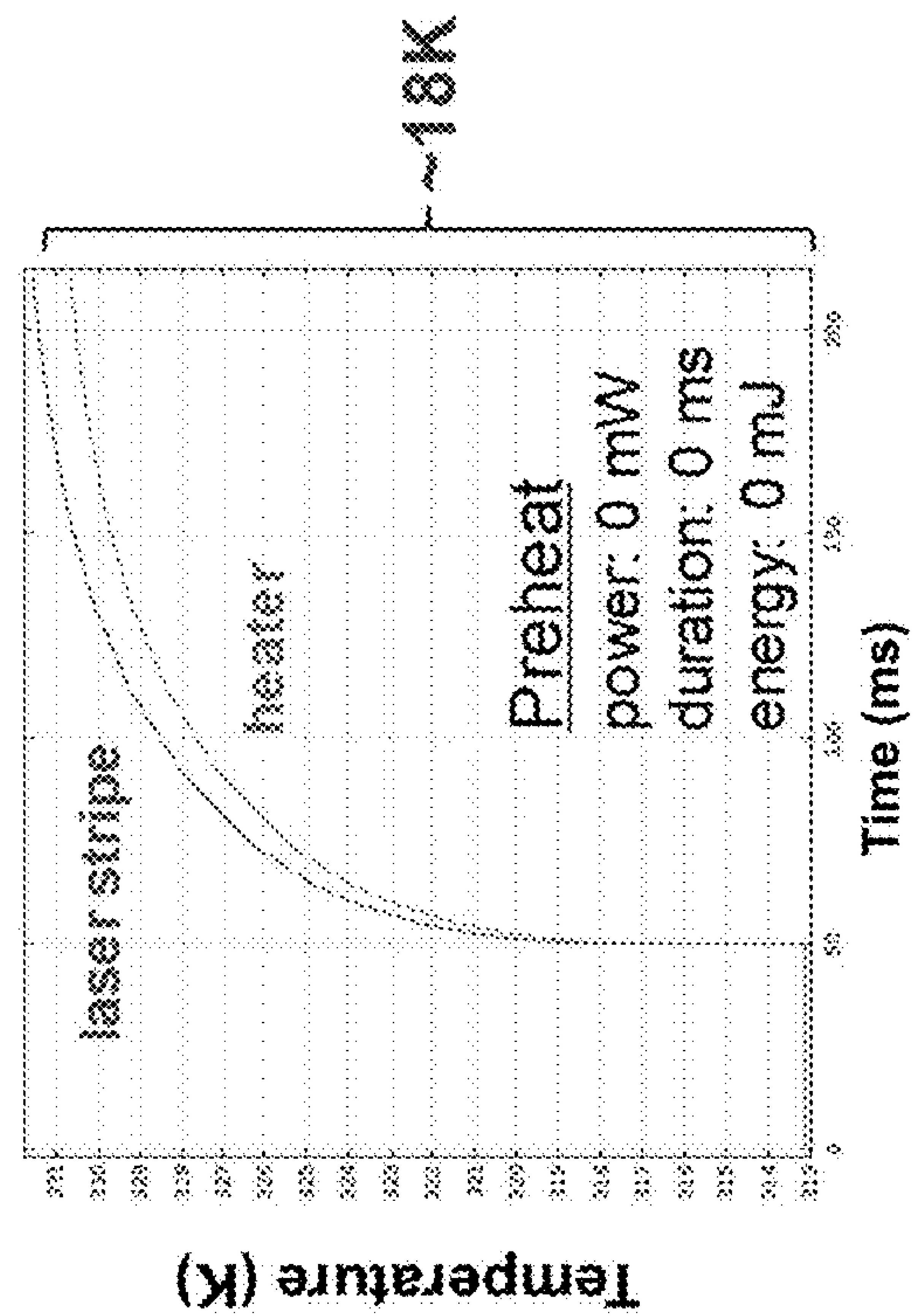


FIGURE 11B

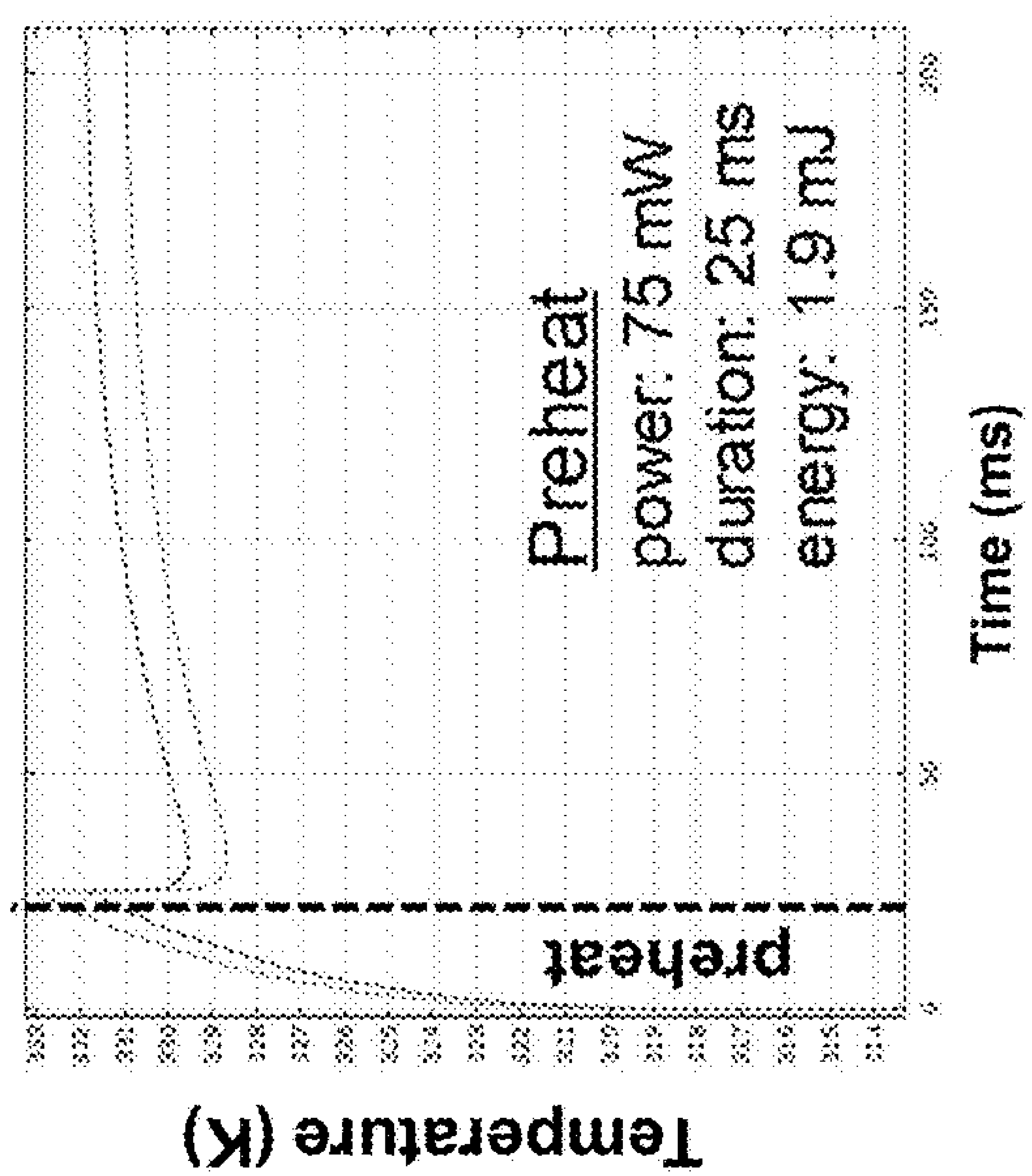


FIGURE 11C

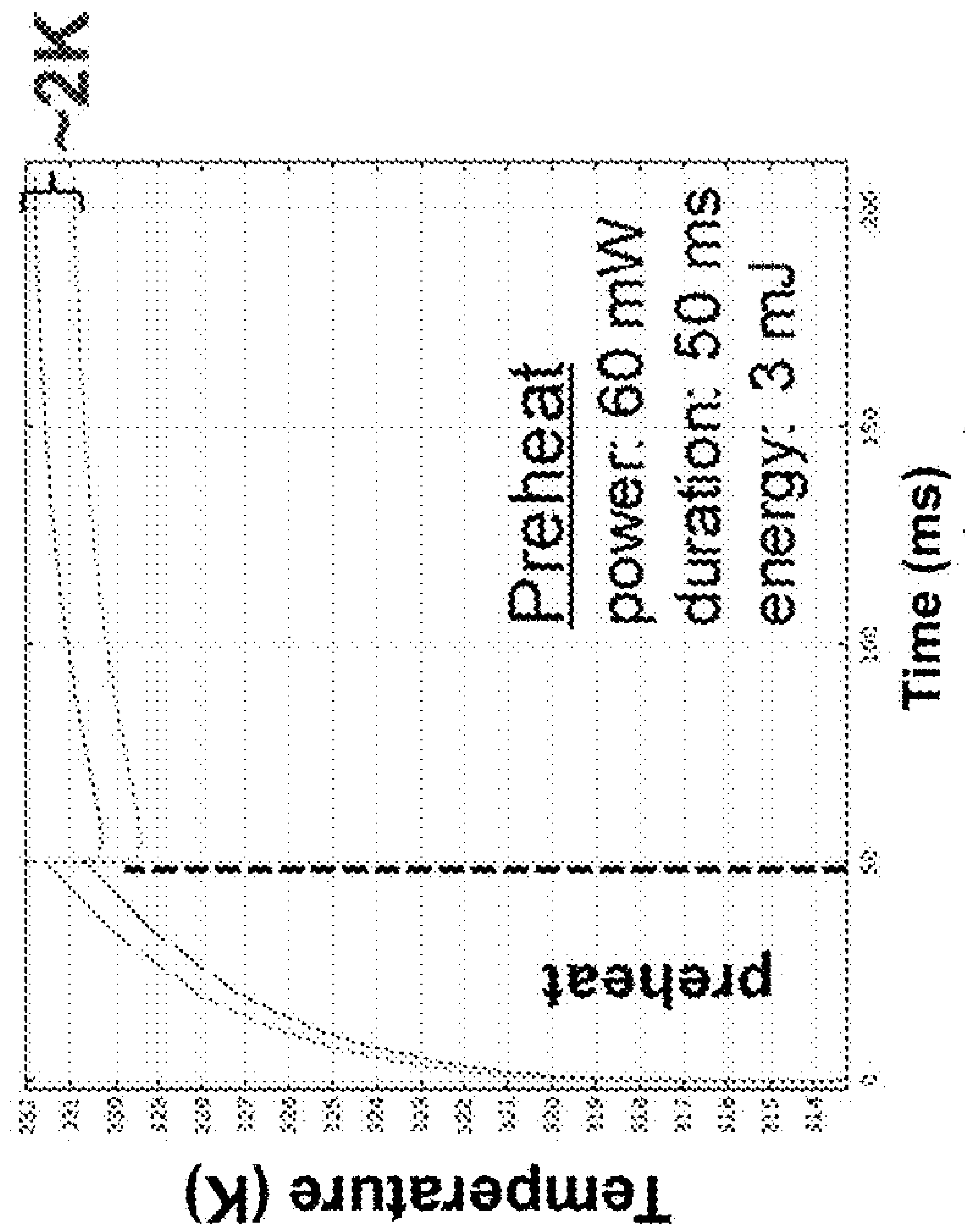
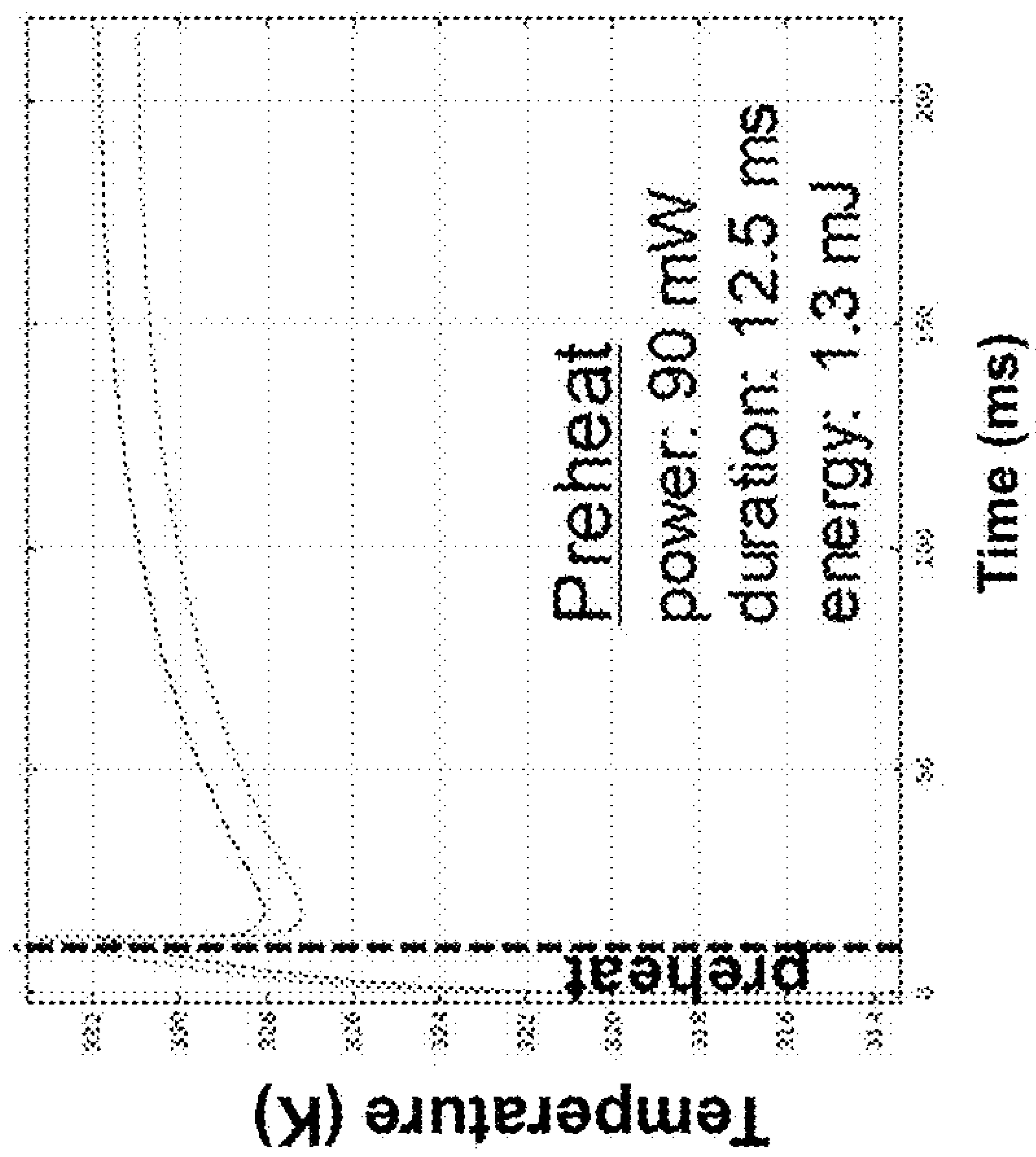


FIGURE 11D



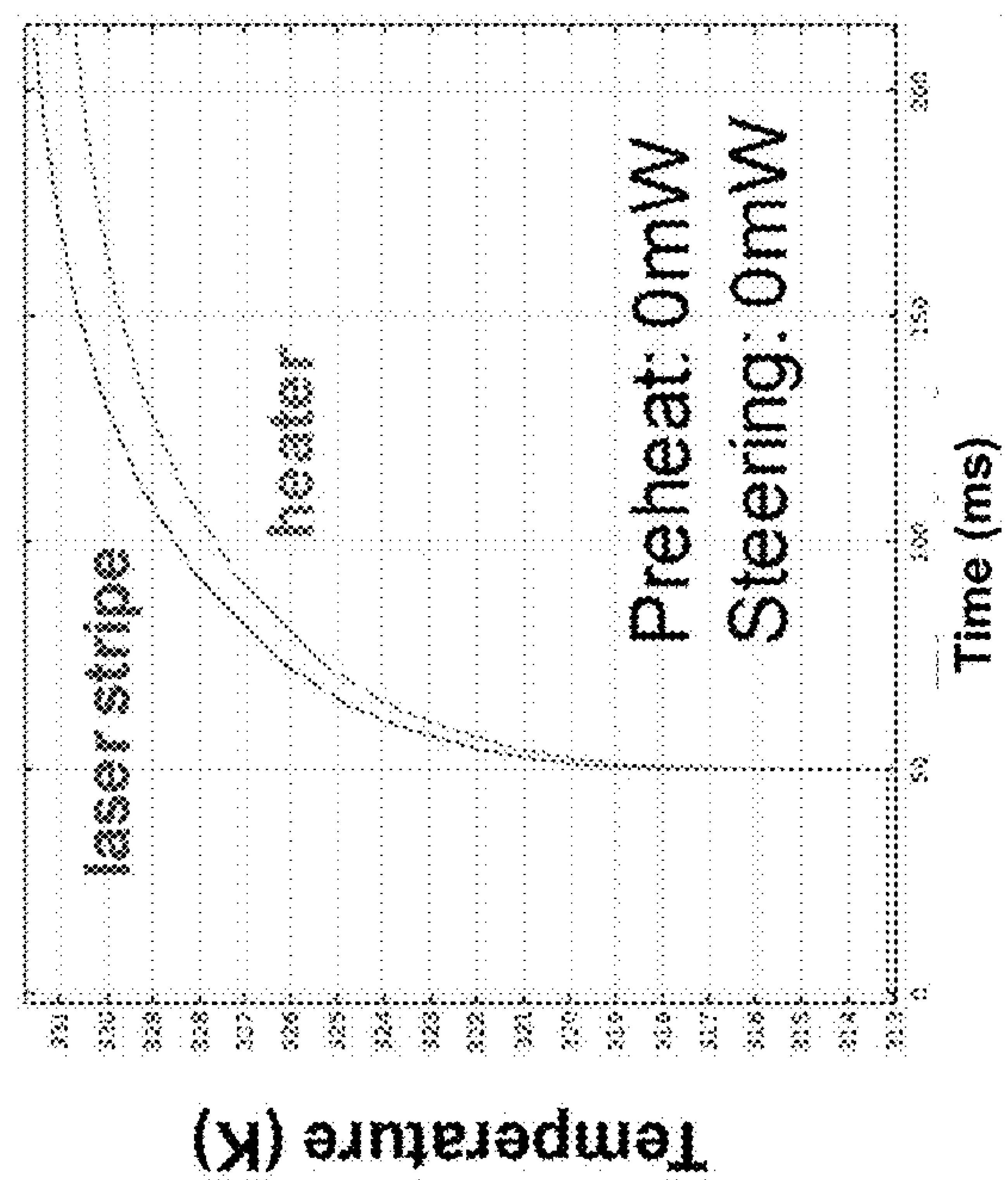


FIGURE 12A

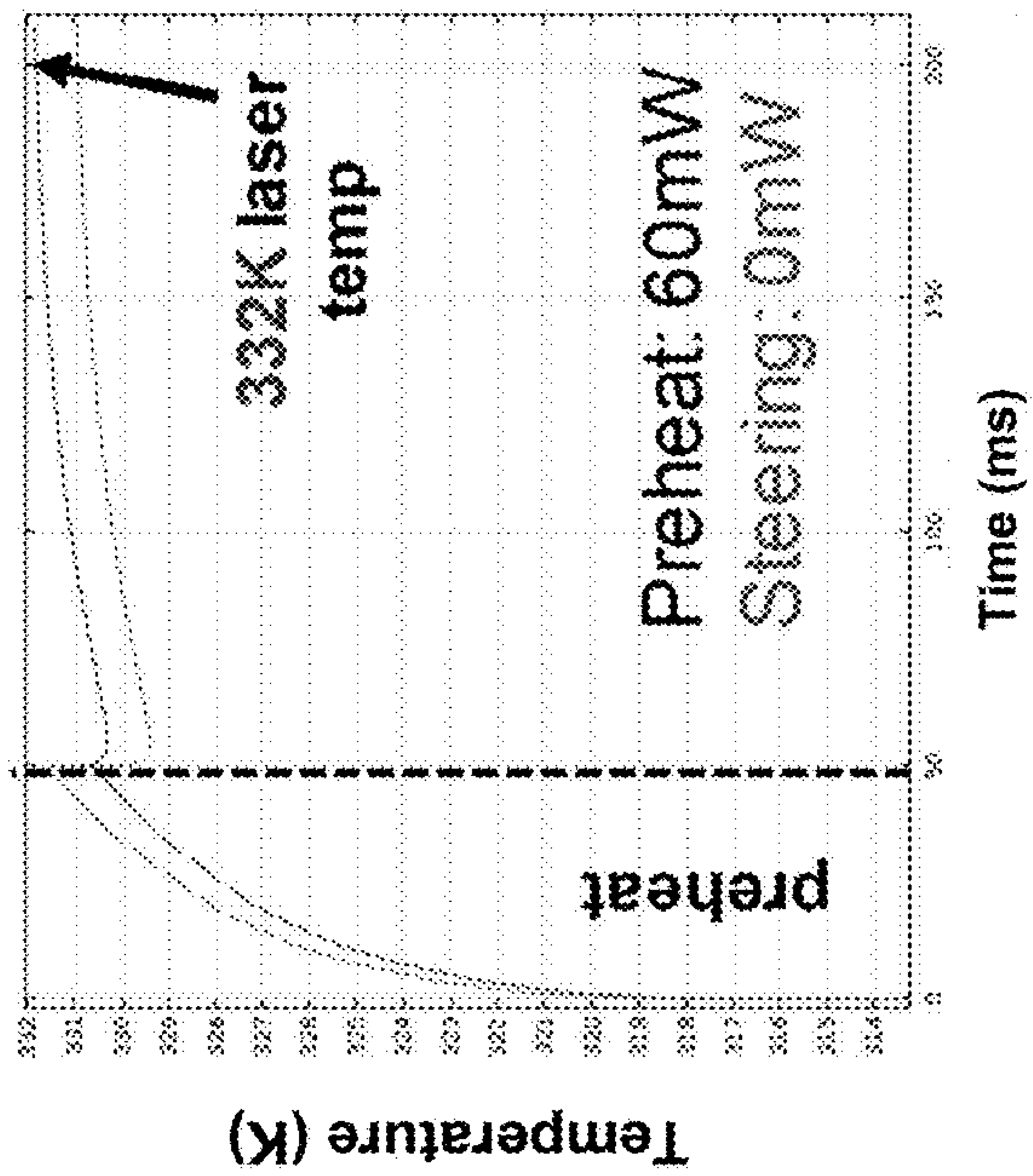


FIGURE 12B

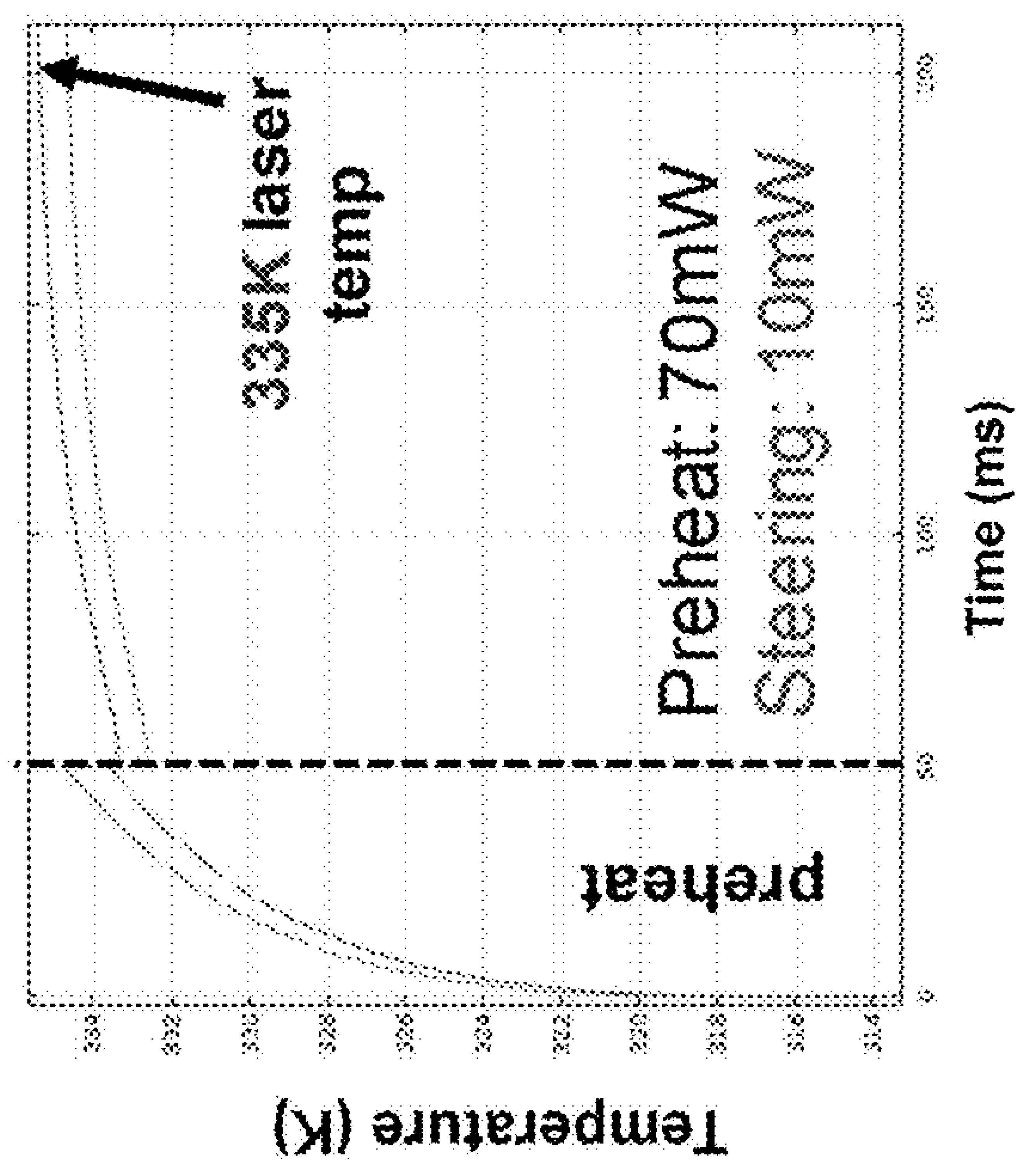


FIGURE 12C

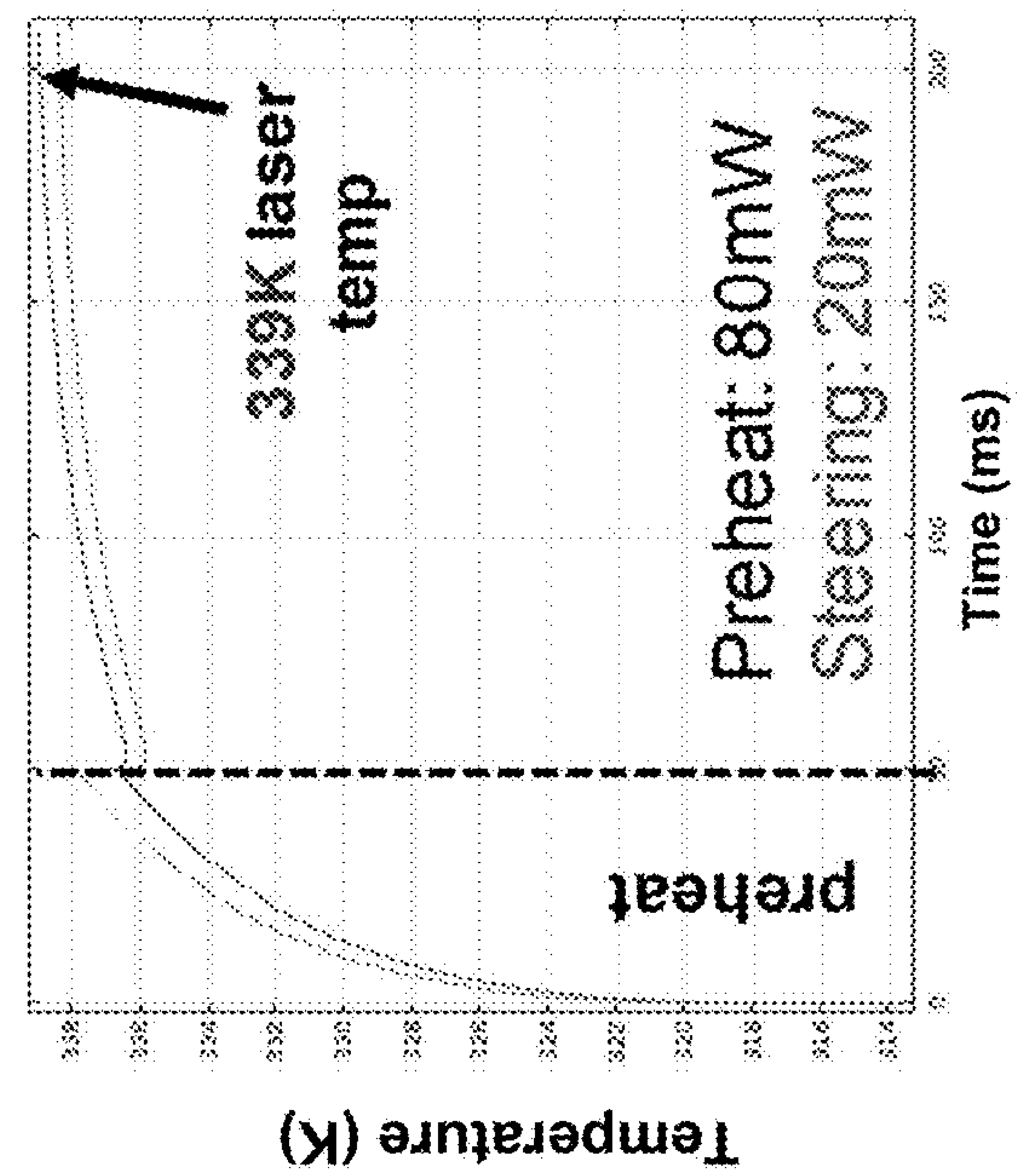


FIGURE 12D

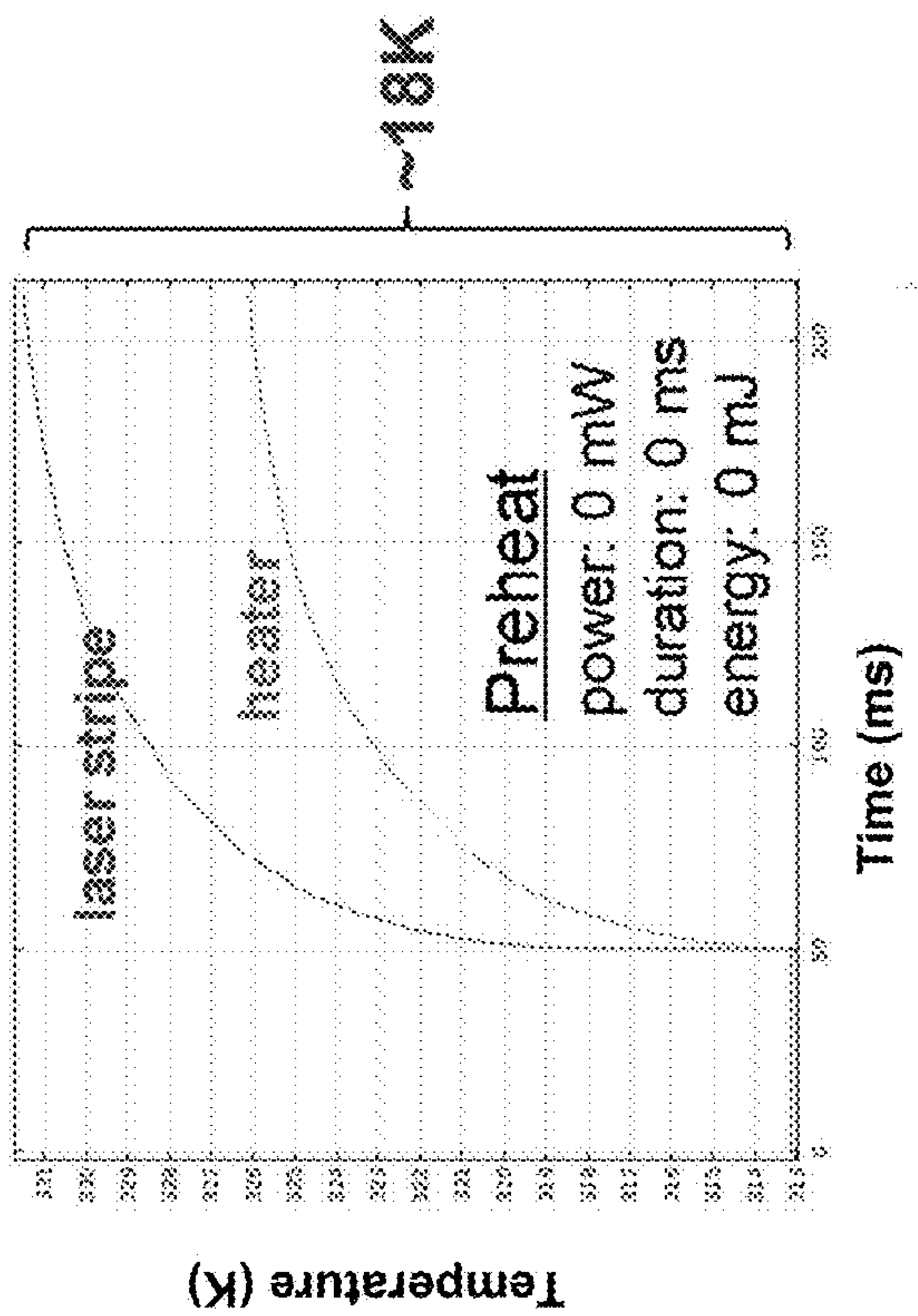


FIGURE 13A

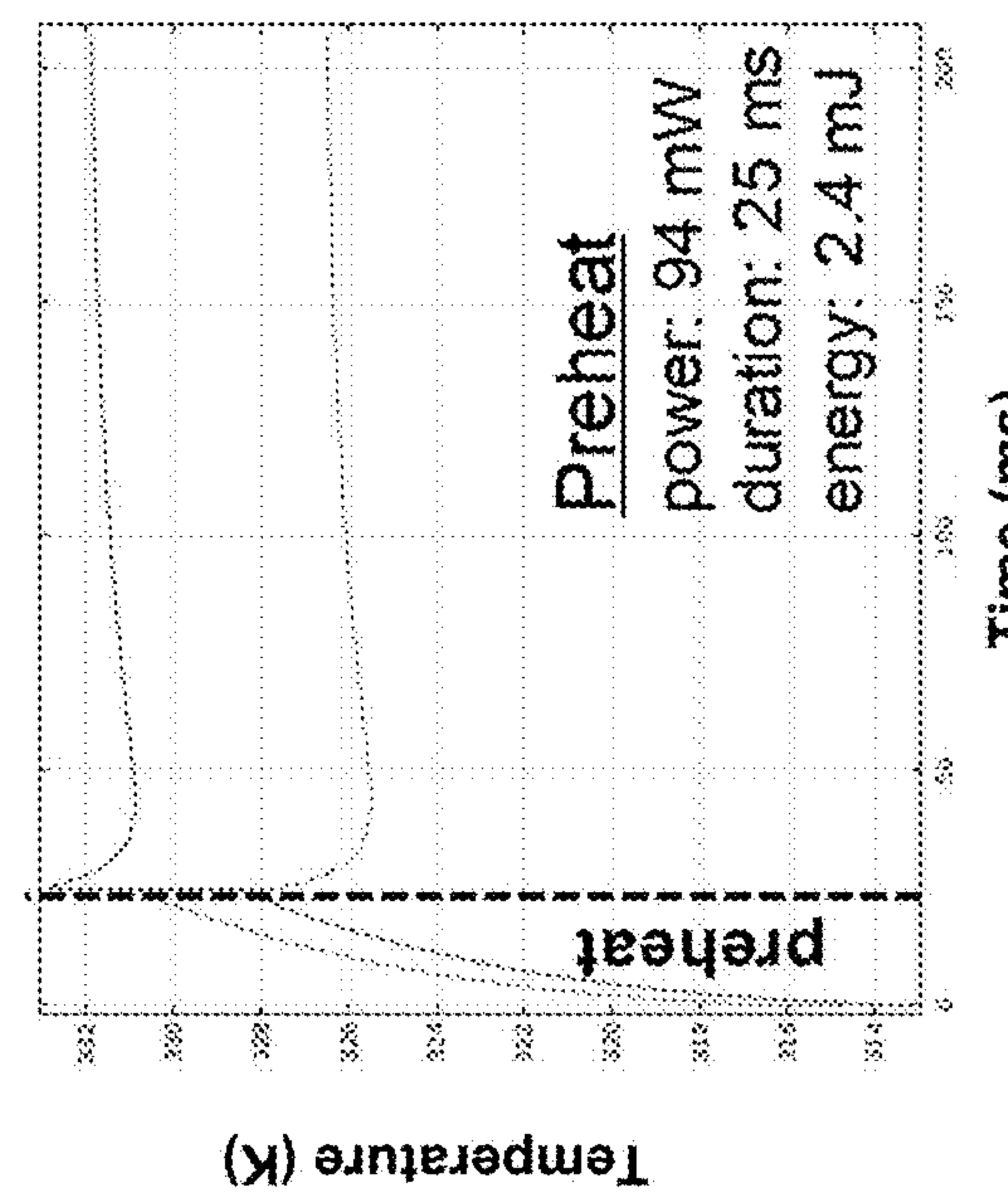


FIGURE 13B

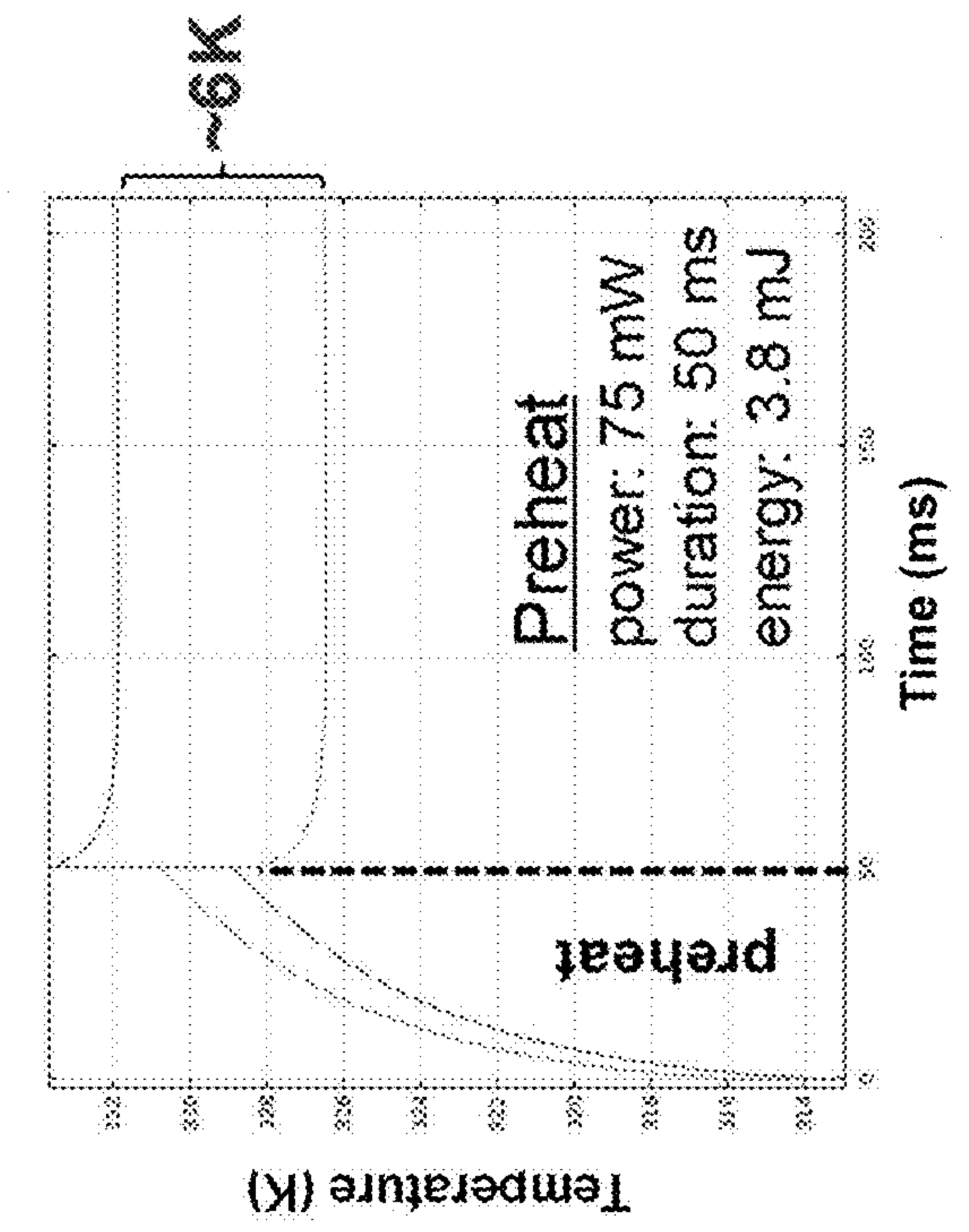


FIGURE 13C

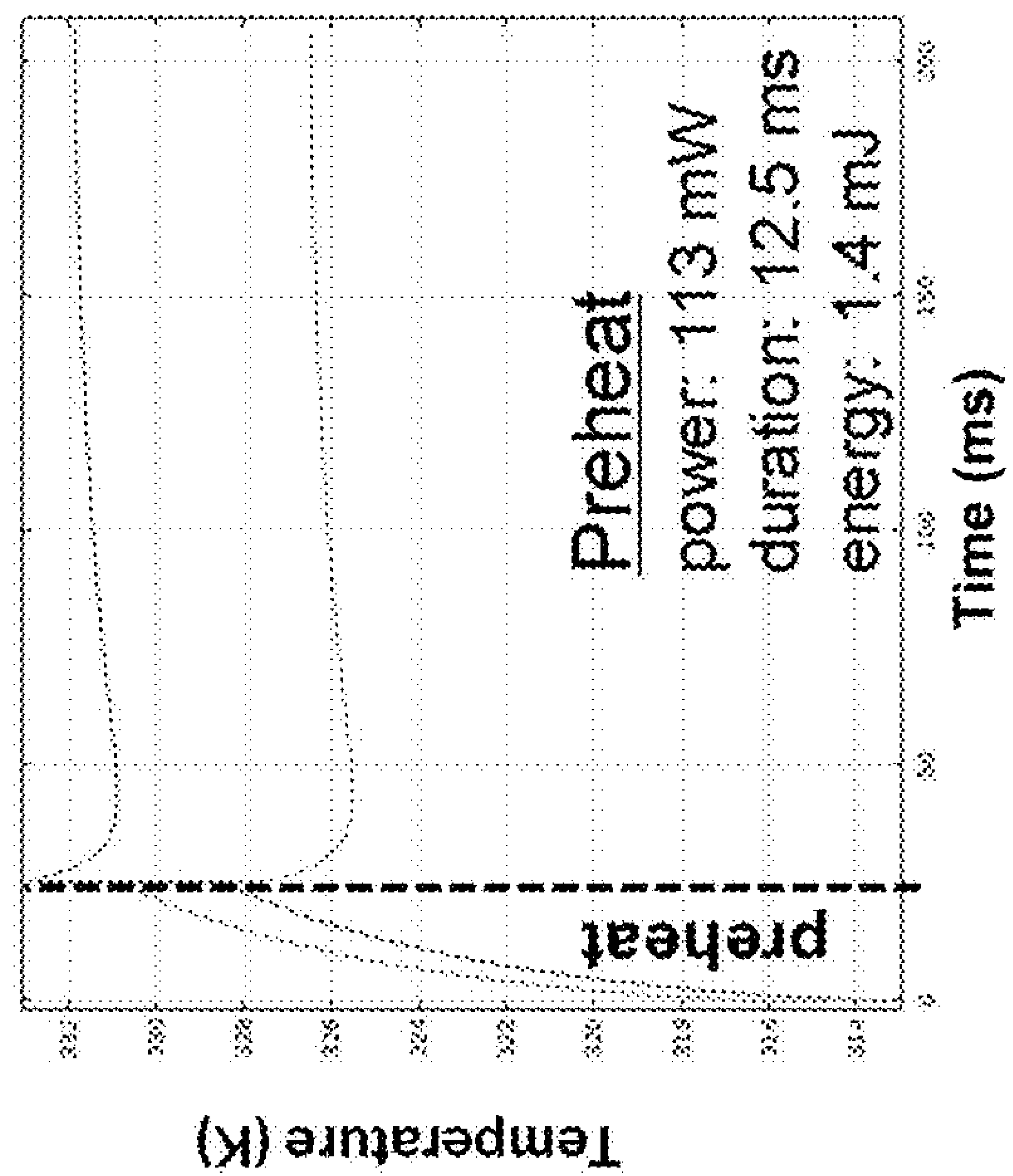


FIGURE 13D

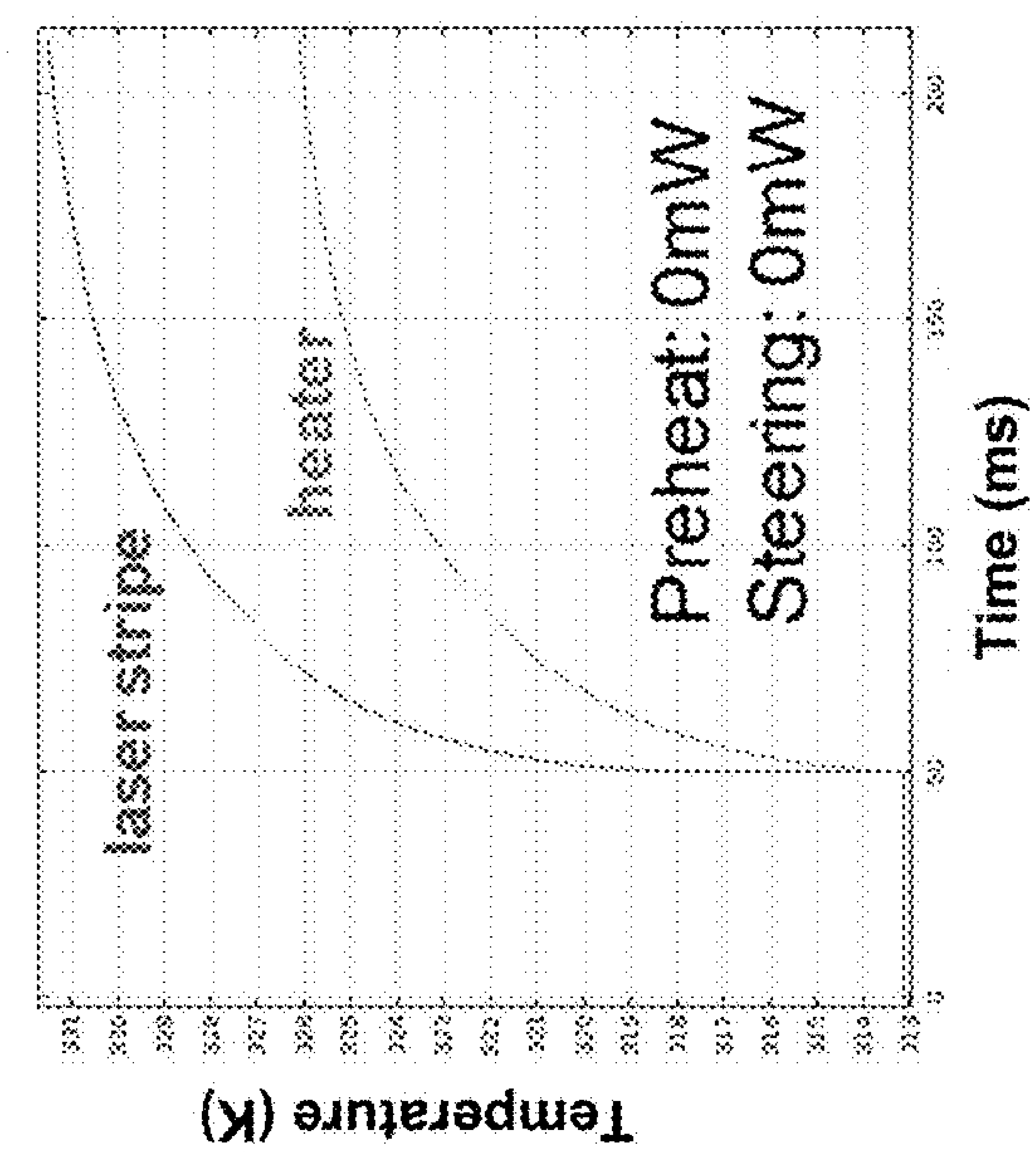


FIGURE 14A

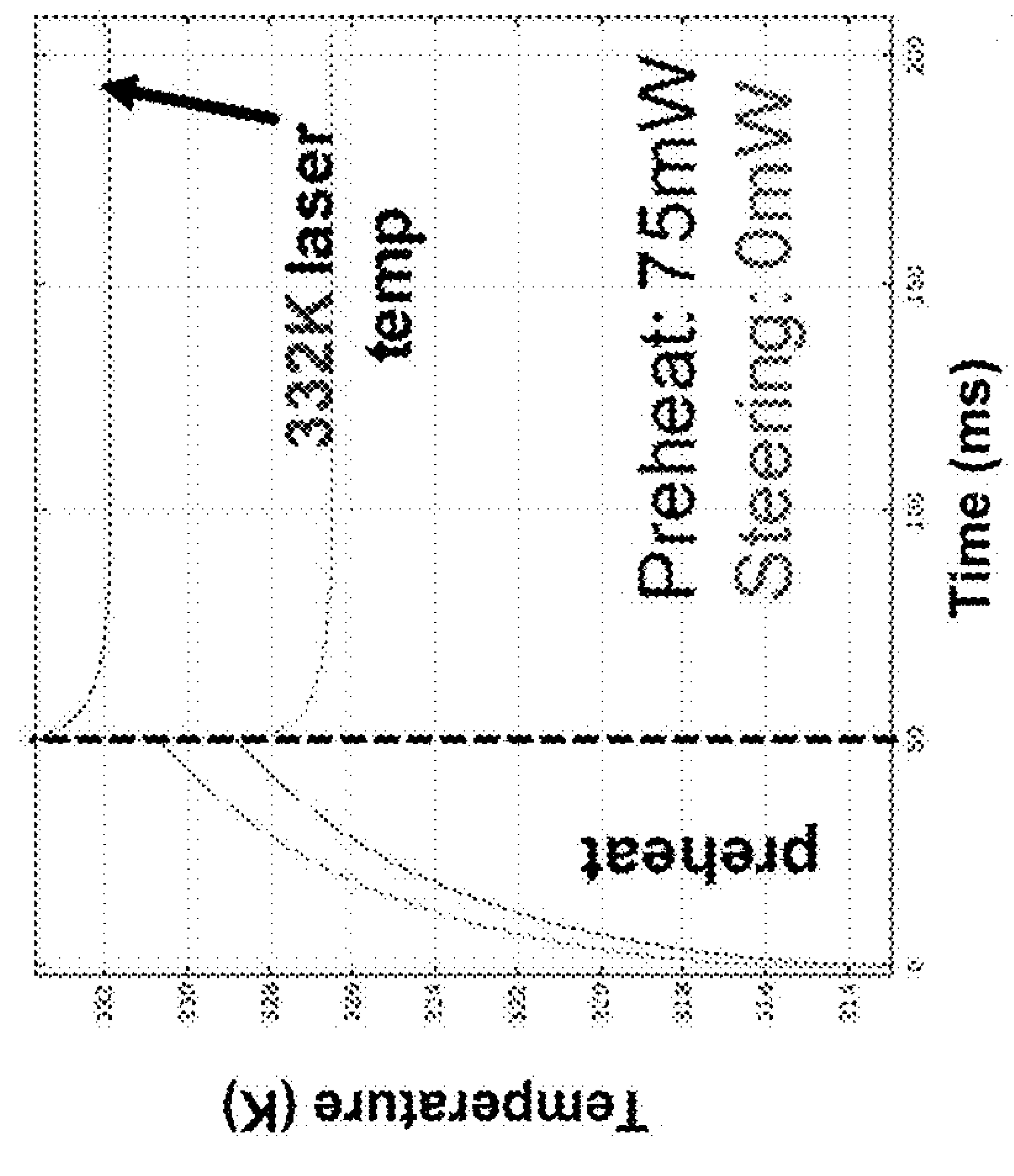


FIGURE 14B

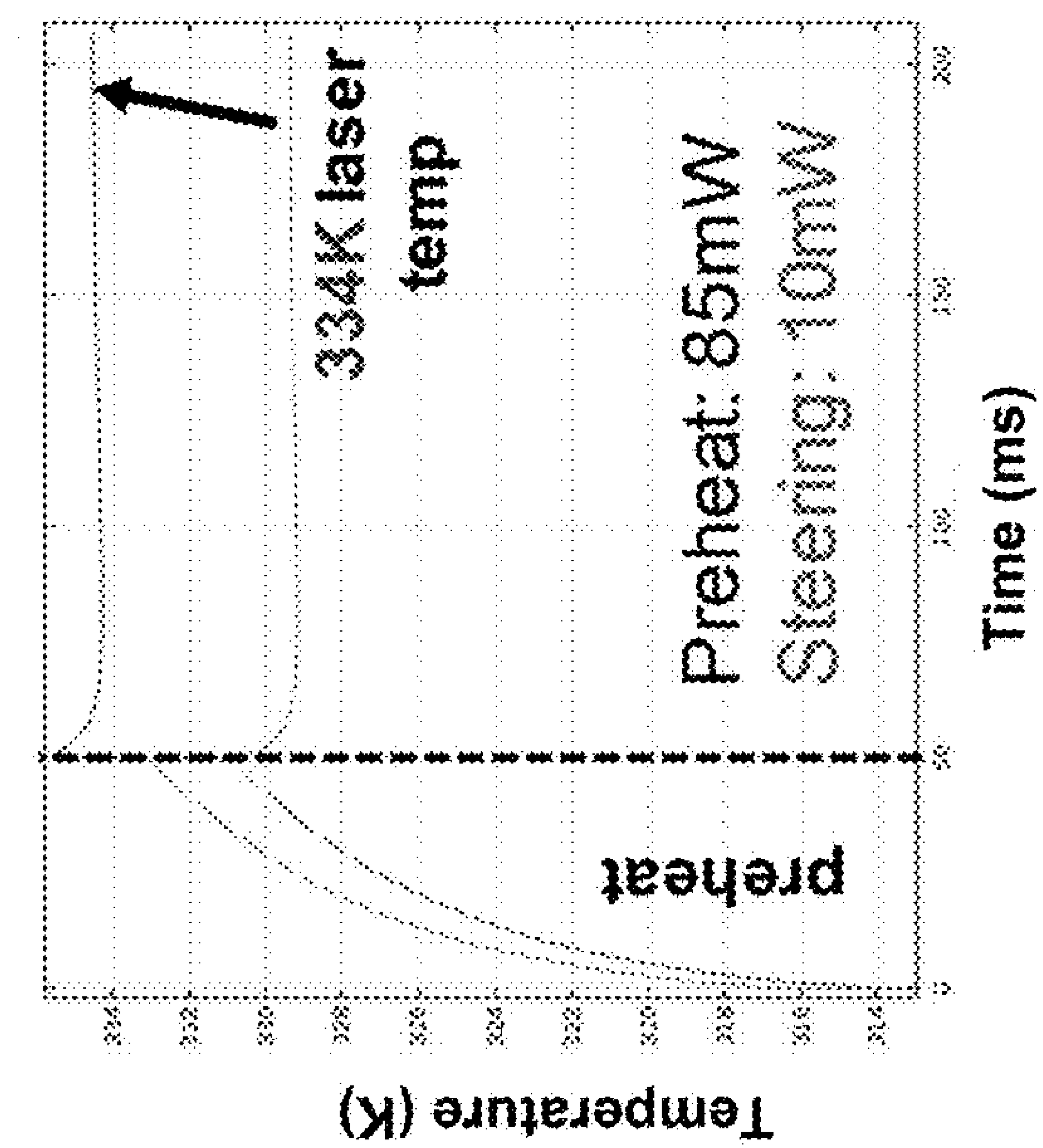


FIGURE 14C

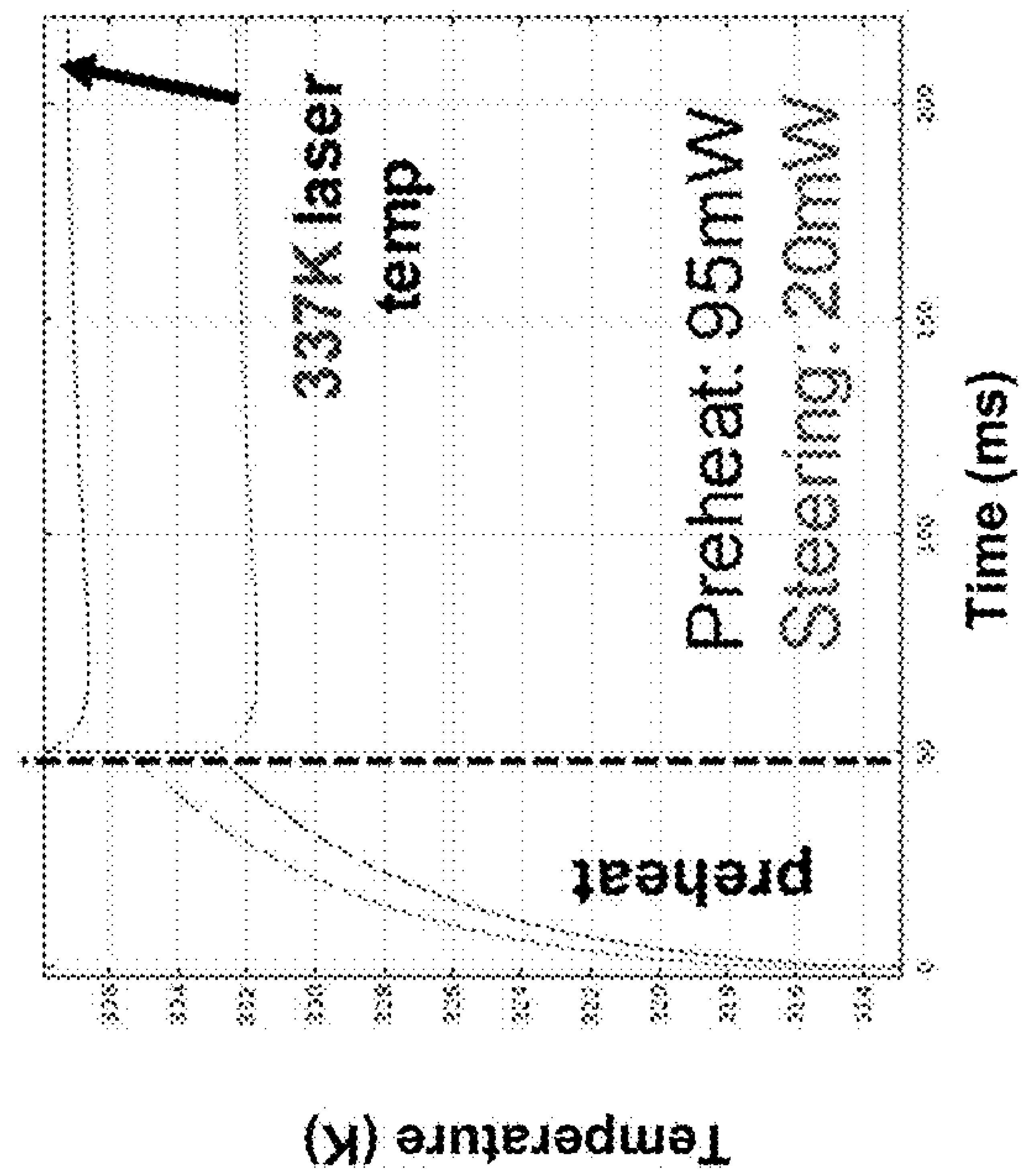


FIGURE 14D

FIGURE 15

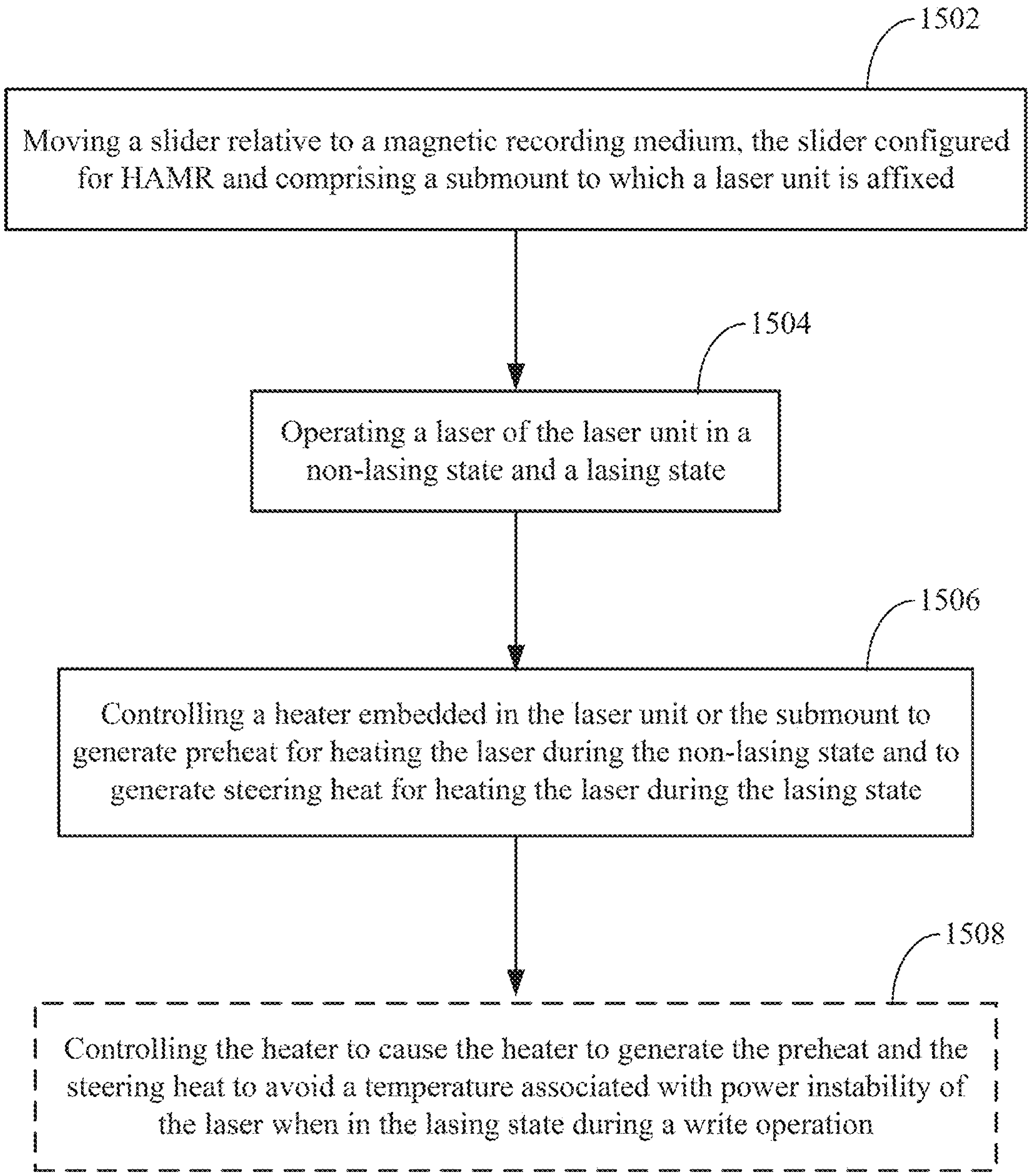
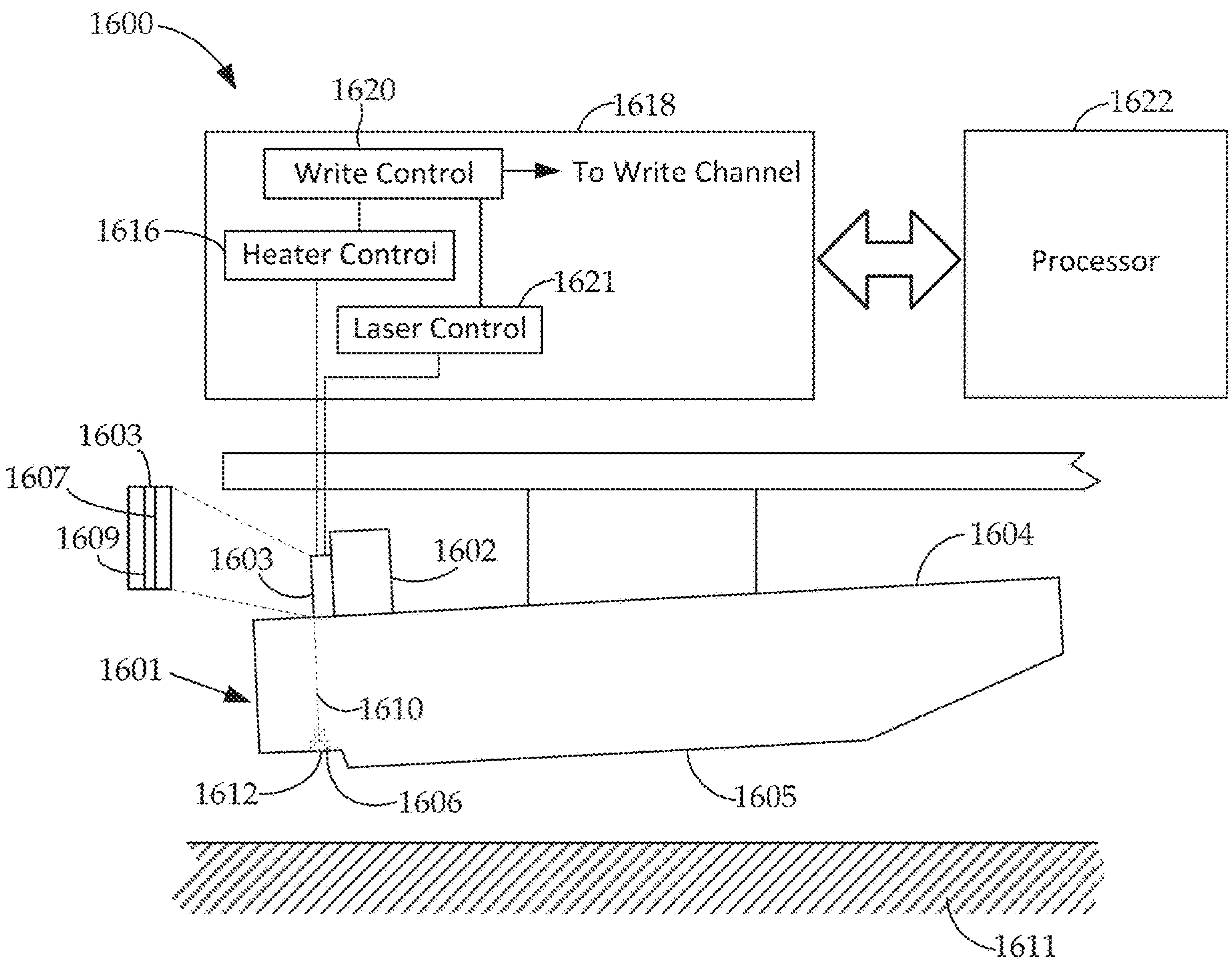

1502
Moving a slider relative to a magnetic recording medium, the slider configured for HAMR and comprising a submount to which a laser unit is affixed
1504
Operating a laser of the laser unit in a non-lasing state and a lasing state
1506
Controlling a heater embedded in the laser unit or the submount to generate preheat for heating the laser during the non-lasing state and to generate steering heat for heating the laser during the lasing state
1508
Controlling the heater to cause the heater to generate the preheat and the steering heat to avoid a temperature associated with power instability of the laser when in the lasing state during a write operation

FIGURE 16



1600
1620
1618
1622
Write Control
To Write Channel
1616
Heater Control
1621
Laser Control
Processor
1603
1607
1609
1603
1602
1604
1601
1610
1612
1606
1605
1611

HEAT-ASSISTED MAGNETIC RECORDING DEVICE INCORPORATING LASER HEATER FOR IMPROVED LASER STABILITY

RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 16/938,101, filed Jul. 24, 2020, which is a continuation of U.S. patent application Ser. No. 16/591,892, filed Oct. 3, 2019, now U.S. Pat. No. 10,783,918, which claims the benefit of Provisional Patent Application Ser. No. 62/744,729 filed on Oct. 12, 2018, which are hereby incorporated herein by reference in their entireties.

SUMMARY

Embodiments are directed to an apparatus comprising a slider configured to facilitate heat assisted magnetic recording and a submount affixed to the slider. A laser unit is affixed to the submount and comprises a laser operable in a non-lasing state and a lasing state. A heater is embedded in the laser unit or the submount. The heater is configured to generate preheat for heating the laser during the non-lasing state and to generate steering heat for heating the laser during the lasing state.

Embodiments are directed to an apparatus comprising a slider configured to facilitate heat assisted magnetic recording and a submount affixed to the slider. A laser unit is affixed to the submount and comprises a laser operable in a non-lasing state and a lasing state. A heater is embedded in the laser unit or the submount. Control circuitry is coupled the laser unit and the heater. The control circuitry is configured to cause the heater to generate preheat for heating the laser during the non-lasing state and to cause the heater to generate steering heat for heating the laser during the lasing state.

Embodiments are directed to a method comprising moving a slider relative to a magnetic recording medium, the slider configured for heat assisted magnetic recording and comprising a submount to which a laser unit is affixed. The method also involves operating a laser of the laser unit in a non-lasing state and a lasing state. The method further involves controlling a heater embedded in the laser unit or the submount to generate preheat for heating the laser during the non-lasing state and to generate steering heat for heating the laser during the lasing state.

The above summary is not intended to describe each disclosed embodiment or every implementation of the present disclosure. The figures and the detailed description below more particularly exemplify illustrative embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

Throughout the specification reference is made to the appended drawings, where like reference numerals designate like elements, and wherein:

FIG. **1** shows a heat-assisted magnetic recording (HAMR) slider in accordance with various embodiments;

FIG. **2** shows a HAMR slider in accordance with various embodiments;

FIG. **3** shows a temperature versus time plot for a representative laser of a HAMR slider in accordance with various embodiments;

FIG. **4** shows a native laser-temperature variation of a representative HAMR laser for short time frames in accordance with various embodiments;

FIG. **5** shows a native laser-temperature variation of a representative HAMR laser for short time frames in accordance with various embodiments;

FIG. **6** illustrates a laser heating apparatus for use with a HAMR slider in accordance with various embodiments;

FIG. **7** illustrates a laser heating apparatus for use with a HAMR slider in accordance with various embodiments;

FIG. **8** illustrates a laser heating apparatus for use with a HAMR slider in accordance with various embodiments;

FIGS. **9** and **10** are plots demonstrating the ability of the laser heating apparatus shown in FIG. **6** to reduce short-time frame variation in laser temperature between laser-on and laser-off events;

FIGS. **11**A-**11**D show the effects of preheat power and duration on laser temperature as a function of time using the laser heating apparatus illustrated in FIG. **6**;

FIGS. **12**A-**12**D show the effects of preheat power and duration and steering heating on laser temperature as a function of time using the laser heating apparatus illustrated in FIG. **6**;

FIGS. **13**A-**13**D show the effects of preheat power and duration on laser temperature as a function of time using the laser heating apparatus illustrated in FIG. **8**;

FIGS. **14**A-**14**D show the effects of preheat power and duration and steering heating on laser temperature as a function of time using the laser heating apparatus illustrated in FIG. **8**;

FIG. **15** is a flow chart showing processes for heating a laser of a heat assisted magnetic recording slider in accordance with various embodiments; and

FIG. **16** is a schematic view of a representative HAMR apparatus and related components that can utilize heating of a laser to reduce laser output power instability according to various embodiments.

The figures are not necessarily to scale. Like numbers used in the figures refer to like components. However, it will be understood that the use of a number to refer to a component in a given figure is not intended to limit the component in another figure labeled with the same number.

DETAILED DESCRIPTION

The present disclosure generally relates to heat-assisted magnetic recording, also referred to as energy-assisted magnetic recording (EAMR), thermally-assisted magnetic recording (TAMR), and thermally-assisted recording (TAR). This technology uses a laser source and a near-field transducer (NFT) to heat a small spot on a magnetic disk during recording. The heat lowers magnetic coercivity at the spot, allowing a write transducer to change the orientation of a magnetic domain at the spot. Due to the relatively high coercivity of the medium after cooling, the data is less susceptible to superparamagnetic effects that can lead to data errors.

Embodiments of a HAMR slider **100** are illustrated in FIGS. **1** and **2**. As shown, the head **100** (also referred to as a slider) includes a light source (e.g., a laser) **102** located proximate a trailing edge surface **104** of the slider body **105**. The laser **102** is shown to include a laser stripe **102***a* in accordance with various embodiments. An optical wave (e.g., a laser beam) generated by the laser **102** is delivered to an NFT **112** via an optical waveguide **110**. The NFT **112** is aligned with a plane of an air bearing surface (ABS) **114** of the head **100**, and one edge of a read/write head **113** is on the ABS **114**. While the representative embodiments of FIGS. **1** and **2** show the waveguide **110** integrated with the head **100**, any type of light delivery configuration may be used. The laser **102** can be implemented as any type of semiconductor laser (e.g., laser diode, optically pumped semiconductor laser, quantum well laser).

The read/write head **113** includes at least one writer and at least one reader. In some embodiments, multiple writers (e.g., two writers) and multiple readers (e.g., three readers) can be incorporated into the read/write head **113**. The ABS **114** faces, and is held proximate to, a surface **116** of a magnetic medium **118** during device operation. The ABS **114** is also referred to as a media-facing surface. The laser **102** in this representative example may be an integral, edge emitting device, although it will be appreciated that any source of electromagnetic energy may be used. For example, a surface emitting laser (SEL), instead of an edge emitting laser, may be used as the laser source **102**. A laser **102** may also be mounted alternatively to other surfaces of the head **100**, such as the trailing edge surface **104**.

According to various embodiments, a heater **103** is thermally coupled to the laser **102**. For example, the heater **103** can be situated in close proximity to, or incorporated as a component of, the laser **102**. In various embodiments, the heater **103** includes one or a multiplicity of heating elements (referred to herein generally as heaters). In FIG. **1**, the laser **102** and heater **103** are shown coupled to the slider body **105** via a submount **108**. The submount **108** can be used to orient and affix the laser **102** (e.g., an edge-emitting laser) so that its output is directed downwards (negative y-direction in the figure). An input surface of the slider body **105** may include a grating, an optical coupler, or other coupling features to receive light from the laser **102**. In some embodiments, the heater **103** is incorporated in or on the submount **108** that couples the laser **102** to the slider body **105**. For example, one or more of the heaters **103** can be affixed to, or incorporated along, a surface of the submount **108** that contacts a surface of the laser **102**. As is shown in FIG. **1**, a heater **103*a*** can be a heater of the submount **108** which is situated in abutment with the laser **102**. The heater **103*a*** can also be located on or in the laser **102**. Combinations of heater/laser configurations are contemplated (e.g., a laser **102** comprising laser stripe **102*a*** and heaters **103** and **103*a***).

The heater **103**, **103*a*** is configured to heat the laser **102** to improve the stability of output optical power of the laser **102**. According to various embodiments, the heater **103**, **103*a*** is configured to change the temperature of a junction of the laser **102** from a temperature associated with laser output power instability to a temperature associated with laser output power stability. For example, the heater **103**, **103*a*** can be configured to pre-heat the laser **102** during times when the laser **102** is not lasing (e.g., prior to and/or after a write operation) and/or is lasing but not at an optical output sufficient for a write operation. The heater **103**, **103*a*** can also be configured to heat the laser **102** when the laser **102** is lasing during a write operation. During the write operation, the heater **103**, **103*a*** can steer the temperature of the laser away from a temperature associated with laser output power instability and towards a temperature associated with laser output power stability.

When writing with a HAMR device, electromagnetic energy is concentrated onto a small hotspot **119** over the track of the magnetic medium **118** where writing takes place, as is shown in the embodiment of FIG. **2**. The light from the laser **102** propagates to the NFT **112**, e.g., either directly from the laser **102** or through a mode converter or by way of a focusing element. FIG. **2**, for example, shows an optical coupler **107** adjacent the laser **102**, which is configured to couple light produced from the laser to the waveguide **110**.

As a result of what is known as the diffraction limit, optical components cannot be used to focus light to a dimension that is less than about half the wavelength of the light. The lasers used in some HAMR designs produce light with wavelengths on the order of 700-1550 nm, yet the desired hot spot **119** is on the order of 50 nm or less. Thus, the desired hot spot size is well below half the wavelength of the light. Optical focusers cannot be used to obtain the desired hot spot size, being diffraction limited at this scale. As a result, the NFT **112** is employed to create a hotspot on the media.

The NFT **112** is a near-field optics device configured to generate local surface plasmon resonance at a designated (e.g., design) wavelength. The NFT **112** is generally formed from a thin film of plasmonic material on a substrate. In a HAMR slider **100**, the NFT **112** is positioned proximate the write pole **226** of the read/write head **113**. The NFT **112** is aligned with the plane of the ABS **114** parallel to the surface **116** of the magnetic medium **118**. The waveguide **110** and optional mode converter **107** and/or other optical element directs electromagnetic energy **120** (e.g., laser light) onto the NFT **112**. The NFT **112** achieves surface plasmon resonance in response to the incident electromagnetic energy **120**. The plasmons generated by this resonance are emitted from the NFT **112** towards the magnetic medium **118** where they are absorbed to create a hotspot **119**. At resonance, a high electric field surrounds the NFT **112** due to the collective oscillations of electrons at the metal surface (e.g., substrate) of the magnetic medium **118**. At least a portion of the electric field surrounding the NFT **112** gets absorbed by the magnetic medium **118**, thereby raising the temperature of a spot **119** on the medium **118** to the Curie temperature as data is being recorded.

FIG. **2** shows a detailed partial cross-sectional view of an embodiment of the HAMR slider **100** in accordance with various embodiments. The waveguide **110** includes a layer of core material **210** surrounded by first and second cladding layers **220** and **230**. The first cladding layer **220** is shown proximate the NFT **112** and the write pole **226**. The second cladding layer **230** is spaced away from the first cladding layer **220** and separated therefrom by the waveguide core **210**. The core layer **210** and cladding layers **220** and **230** may be fabricated from dielectric materials, such as optical grade amorphous material with low thermal conductivities. The first and second cladding layers **220** and **230** may each be made of the same or a different material. The materials are selected so that the refractive index of the core layer **210** is higher than refractive indices of the cladding layers **220** and **230**. This arrangement of materials facilitates efficient propagation of light through the waveguide core **210**. Optical focusing elements (not shown) such as mirrors, lenses, etc., may be utilized to concentrate light onto the NFT **112**. These and other components may be built on a common substrate using wafer manufacturing techniques known in the art. The waveguide **110** may be configured as a planar waveguide or channel waveguide.

According to some embodiments, the head **100** includes one or more sensors, such as the sensor **201** shown in FIG. **2**. In some embodiments, the sensor **201** can be a contact sensor configured to sense for one or more of head-medium contact, thermal asperities, and voids of a magnetic recording medium. In other embodiments, the sensor **201** can be a bolometer or a combined contact sensor/bolometer. The sensor **201** can be configured to produce a response to laser light that is used to detect laser output power instability, such as mode hops, in accordance with various embodiments. The sensor **201** can be a resistive sensor that can be implemented as a thermal sensor, such as a resistive temperature sensor (e.g., TCR sensor). The sensor **201** can be a thermo-resistive/electric sensor or a piezoresistive/electrical sensor, for example. By way of further example, the sensor **201** can be a thermocouple or a thermistor. The sensor **201** can be situated at or near the ABS **114** and proximate the NFT **112**. As such, the sensor **201** can also serve as a temperature sensor for the NFT **112** and as a head-medium/asperity contact sensor.

The output of a laser used in a HAMR drive is temperature sensitive and susceptible to self-heating. During a write operation, for example, laser heating can vary the junction temperature of the laser, causing a shift in laser emission wavelength, leading to a change of optical feedback from the optical path in the slider to the cavity of the laser, a phenomenon that is known to lead to mode hopping and/or power instability of the laser. Mode hopping is particularly problematic in the context of lasers emitting primarily a single frequency. Under some external influences, such a laser may operate on one resonator mode (e.g., produce energy with a first wavelength) for some time, but then suddenly switch to another mode (produce energy, often with different magnitude, with a second wavelength) performing "mode hopping." Temperature variation is known to cause mode hopping in lasers. Mode hopping is problematic for HAMR applications, as mode hopping leads to laser output power jumping and magnetic transition shifting from one data bit location (e.g., one block of data) to another. It is noted that the laser output power can jump in either direction (higher or lower) with a mode hop and that a jump in either direction is undesirable. Large transition shifts in a data bit location due to a mode hop may not be recoverable by channel decoding, resulting in error bits. Also, writing width varies with laser power so power fluctuations can lead to erasure of adjacent tracks or undesirably narrow written tracks. Heating the laser **102** by the heater **103**, such as prior to and/or during a write operation, reduces temperature fluctuations at the laser junction, which serves to reduce the likelihood of mode hopping.

According to various implementations, and with reference to FIGS. **2** and **3**, when the laser **102** heats up in response to a write request, instabilities in the system may arise. These instabilities may occur at specific critical temperatures (T_{Cr}). These critical temperatures may be different for every laser and/or may depend on various factors such as the current environment, for example. FIG. **3** shows the temperature versus time for a representative laser. In this example, there are five critical temperatures **310**, **320**, **330**, **340**, **350**. When heating up a laser, the temperature rises quickly at first and then starts to level off. The critical temperatures are substantially periodic. Thus, more critical temperatures are experienced in a short period of time at the beginning of the heat-up process because the system is heating up more quickly than at later times. Therefore, it can be observed that the higher the slope of the temperature rise in time, the higher the probability of reaching a higher number of critical temperatures.

If the system can start pre-heating the laser to a temperature before the write process starts, the number of possible transitions though critical temperatures is reduced. If a pre-heat takes place and the system is heated to temperature **335** shown in FIG. **3**, for example, the first three critical temperatures **310**, **320**, **330** are reached before the write operation starts and only two critical temperatures **340**, **350** are experienced during the write operation. A system without a laser heating pre-heat feature would experience all five **310**, **320**, **330**, **340**, **350** critical temperatures in this example. Moreover, if the system can heat the laser during the write process, the laser temperature can be steered away from a critical temperature and into a region of laser output power stability between critical temperatures. For example, assume that a laser is at temperature **345** shown in FIG. **3** during a write operation and approaching critical temperature **350** during the write operation. Because the laser temperature **345** is approaching the critical temperature **350**, the system may apply steering heat during the write operation in order to elevate the temperature of the laser away from the critical temperature **350** and to a higher temperature **360** associated with laser output power stability. The system preferably repeats the pre-heating and steering heat generation processes for subsequent write operations.

FIGS. **4** and **5** illustrate the native laser-temperature variation of a representative laser of a HAMR head without heating by a heater. It is noted that, for FIGS. **4** and **5**, the laser turns on at 50 mW at time=0 sec. It is also noted that 50 mW represents thermal power absorbed in the laser, not the laser light output power. This convention is used in the discussion provided hereinbelow.

FIG. **4** shows the native laser-temperature variation of the laser for short time frames (e.g., ~15 μs for each of a sequence of servo wedges). The laser temperature variation between laser-on and laser-off conditions is about 1.6 K in the scenario shown in FIG. **4**. FIG. **5** shows the native laser-temperature variation of the laser for a long time frame (e.g., multiple disk revolutions). The laser temperature variation between laser-on and laser-off conditions is about 18 K in the scenario shown in FIG. **5**.

Provision of a heater to heat a laser of a HAMR head serves to achieve two primary objectives. The first objective is to bring the laser to its steady-state temperature prior to using the laser for writing. This function is referred to as "preheating," as discussed above. The second objective is to increase the laser temperature to the nearest stable operating temperature zone. This function is referred to as "steering," as discussed above. In some embodiments, the targeted steering range is about 5 K.

Embodiments of the disclosure are directed to a laser heating apparatus and method that can provide pre-heat (prior to a write operation) and/or steering heat (during a write operation) to the laser in a manner that improves the stability of output optical power of the laser.

Embodiments are directed to three different laser heating apparatus configurations, each of which can provide pre-heat (prior to a write operation) and/or steering heat (during a write operation) to the laser in a manner that improves the stability of output optical power of the laser.

FIG. **6** illustrates a laser heating apparatus in accordance with various embodiments. FIG. **6** shows a slider body **605** and a submount **608** affixed to the slider body **605**. A laser **602** is mounted to the submount **608** and includes a laser stripe **602***a*. In some embodiments, the laser **602** can be incorporated in a package referred to herein as a laser unit, which is mounted to the submount **608** and optically coupled to integrated optics of the slider body **605**. The laser unit can include a substrate, the laser **602** (e.g., which includes a laser stripe **602***a*) on the substrate, and an enclosure around the laser **602** and substrate. In some configurations, the laser unit enclosure can house or support a first electrical contact, a substrate, an active layer between P and N cladding layers, a second electrical contact, and an output facet. The laser unit can also incorporate a heater **603** configured to heat the laser stripe **602***a*. According to various embodiments, the laser **602** has a structure in which the current is injected only within a narrow region beneath a stripe contact (shown as laser stripe **602***a*) which is typically several μm wide. This structure provides for a low threshold current and enhanced control of the optical field distribution.

The heater **603** can be a wire or thin metal stripe positioned proximate to, and extending along the length of, the laser stripe **602***a* of the laser **602**. In the embodiment shown in FIG. **6**, the heater **603** is embedded in or otherwise affixed to the laser **602** and positioned about 5 μm from the laser stripe **602***a* (shown as two closely spaced separate linear elements in FIG. **6**).

FIG. **7** illustrates a laser heating apparatus in accordance with various embodiments. FIG. **7** shows a slider body **705** and a submount **708** affixed to the slider body **705**. A laser **702** is mounted to the submount **708** and includes a laser stripe **702***a*. In some embodiments, the laser **702** can be incorporated in a laser unit, details of which are provided above. The heater **703** can be a wire or thin metal stripe positioned proximate to, and extending along the length of, the laser stripe **702***a* of the laser **702**. In the embodiment shown in FIG. **7**, the heater **703** is embedded in or otherwise affixed to the laser **702** and positioned about 50 μm from the laser stripe **702***a*.

FIG. **8** illustrates a laser heating apparatus in accordance with various embodiments.

FIG. **8** shows a slider body **805** and a submount **808** affixed to the slider body **805**. A laser **802** is mounted to the submount **808** and includes a laser stripe **802***a* (not visible in the view of FIG. **8**). In some embodiments, the laser **802** can be incorporated in a laser unit, details of which are provided above. The heater **803** can be a wire or thin metal stripe embedded in the submount **808**. The heater **803** can have a length equivalent to that of the laser stripe **802***a*. In this embodiment, the heater **803** is embedded in or otherwise affixed to the submount **808**. For example, the heater **803** can be embedded in the submount **808** at a depth of about 5 μm below the submount surface (e.g., ~5 μm below the Under Bump Metallization or UBM). The heater **803** generates heat at the submount **808** which is conducted through the laser **802** (e.g., the laser unit) and to the laser stripe **802***a*. The heater **803** can be separated from the laser stripe **802***a* by a spacing approximately equal to the thickness of the laser **802** plus the thickness of the solder. For example, the heater **803** can be separated from the laser stripe **802***a* by a spacing that ranges from about 40 μm to about 120 μm (e.g., about 80 μm).

Temperature steering, preheat power, and preheat time effects for each of the laser heating apparatus configurations illustrated in FIGS. **6** and **8** are shown in FIGS. **9**-**14**. It is noted that the performance of the laser heating apparatus configuration illustrated in FIG. **7** (heater-laser stripe spacing of 50 μm) is similar to that of the submount heater configuration shown in FIG. **8** and, therefore, is not provided herein.

FIGS. **9** and **10** demonstrate the ability of the laser heating apparatus shown in FIG. **6** to reduce short-time frame variation in laser temperature between laser-on and laser-off events. FIG. **9** shows the native laser-temperature variation of the laser **602** (heater **603** off, no I_{bias} current supplied to the laser) for short time frames (e.g., ~15 μs for each of a sequence of servo wedges). The laser temperature variation between laser-on and laser-off conditions is about 1.6 K in the scenario shown in FIG. **9**. FIG. **10** shows the laser-temperature variation of the laser **602** with the heater **603** on (75 mW during servo, no I_{bias} current supplied to the laser) for the same short time frames as those of FIG. **9**. In FIG. **10**, the laser temperature variation between laser-on and laser-off conditions is dramatically reduced from about 1.6 K (see FIG. **9**) to about 0.5 K. FIG. **10** demonstrates that preheating the laser stripe **602***a* using the proximal heater **603** (at a spacing of ~5 μm) can significantly reduce laser temperature variations between laser-on and laser-off events, and reduce laser temperature ripple even on a microsecond time scale.

FIGS. **11**A-**11**D show the effects of preheat power and duration on laser temperature as a function of time using the laser heating apparatus illustrated in FIG. **6** (spacing of ~5 μm between heater **603** and laser stripe **602***a*). FIG. **11**A shows laser temperature as a function of time with no heater power applied (no preheat, 0 mW). FIGS. **11**B, **11**C, and **11**D show plots of laser temperature versus time for different laser heating scenarios, each differing in terms of heater power (75 mW, 60 mW, 90 mW, respectively), duration (25 ms, 50 ms, 12.5 ms, respectively), and energy (1.9 mJ, 3 mJ, 1.3 mJ). In FIGS. **11**B, **11**C, and **11**D, preheating power was applied from 0 sec to duration, and 50 mW of laser power was applied starting at duration.

For each of these heating scenarios, it can be seen that preheating the laser **602** using the proximal heater **603** significantly reduces the operational laser temperature variation in comparison to the no-heating scenario shown in FIG. **11**A. For example, the ~18 K operational laser temperature variation shown in FIG. **11**A (no laser heating) is reduced to about 2 K in the heating scenario shown in FIG. **11**C. FIGS. **11**A-**11**D demonstrate that a nearly 90% reduction in operational temperature variation of the laser **602** can be achieved using the proximal heater **603**. Moreover, various preheat durations, waveforms, and power can be used.

FIGS. **12**A-**12**D show the effects of preheat power and duration and steering heating on laser temperature as a function of time using the laser heating apparatus illustrated in FIG. **6** (spacing of ~5 μm between heater **603** and laser stripe **602***a*). FIG. **12**A shows laser temperature as a function of time with no heater power applied (no preheat, no steering heat). FIG. **12**B shows a plot of laser temperature versus time with 60 mW of preheat but no steering heating. FIG. **12**C shows a plot of laser temperature versus time with 70 mW of preheat and 10 mW of steering heating. FIG. **12**D shows a plot of laser temperature versus time with 80 mW of preheat and 20 mW of steering heating.

In FIGS. **12**A-**12**D, 50 mW of power was delivered to the laser **602** at 50 ms and afterward. In FIGS. **12**B, **12**C, and **12**D, power delivered to the heater **603** for preheating was applied from 0 sec to 50 ms. Power delivered to the heater **603** for steering was applied from 50 ms onward. FIGS. **12**A-**12**D demonstrate that laser temperature steering can be achieved using the laser heating apparatus shown in FIG. **6**. For example, 14 mW of power delivered to the heater **603** can achieve a targeted 5 K of laser temperature steering. Also, a steering efficiency (laser temperature change per heater power) of 0.35 K/mW can be achieved using the laser heating apparatus shown in FIG. **6**.

FIGS. **13**A-**13**D show the effects of preheat power and duration on laser temperature as a function of time using the laser heating apparatus illustrated in FIG. **8** (heater **803** embedded in submount **808**). FIG. **13**A shows laser temperature as a function of time with no heater power applied (no preheat). FIGS. **13**B, **13**C, and **13**D show plots of laser temperature versus time for different laser heating scenarios, each differing in terms of heater power (94 mW, 75 mW, 113 mW, respectively), duration (25 ms, 50 ms, 12.5 ms, respectively), and energy (2.4 mJ, 3.8 mJ, 1.4 mJ). In FIGS. **13**B, **13**C, and **13**D, preheating power was applied from 0 sec to duration, and 50 mW of laser power was applied starting at duration.

For each of these heating scenarios, it can be seen that preheating the laser **802** using the submount heater **803** significantly reduces the operational laser temperature variation in comparison to the no-heating scenario shown in FIG. **13**A. For example, the ~18 K operational laser temperature variation shown in FIG. **13**A (no laser heating) is reduced to about 6 K in the heating scenario shown in FIG. **13**C. FIGS. **13**A-**13**D demonstrate that a nearly 65% reduction in operational temperature variation of the laser **802** can be achieved using the submount heater **803**. Moreover, various preheat durations, waveforms, and power can be used.

FIGS. **14**A-**14**D show the effects of preheat power and duration and steering heating on laser temperature as a function of time using the laser heating apparatus illustrated in FIG. **8** (submount heater **803** and laser stripe **802***a*). FIG. **14**A shows laser temperature as a function of time with no heater power applied (no preheat, no steering heat). FIG. **14**B shows a plot of laser temperature versus time with 75 mW of preheat but no steering heating. FIG. **14**C shows a plot of laser temperature versus time with 85 mW of preheat and 10 mW of steering heating. FIG. **14**D shows a plot of laser temperature versus time with 95 mW of preheat and 20 mW of steering heating.

In FIGS. **14**A-**14**D, 50 mW of power was delivered to the laser **802** at 50 ms and afterward. In FIGS. **14**B, **14**C, and **14**D, power delivered to the heater **803** for preheating was applied from 0 sec to 50 ms. Power delivered to the heater **803** for steering was applied from 50 ms and onward. FIGS. **14**A-**14**D demonstrate that laser temperature steering can be achieved using the laser heating apparatus shown in FIG. **8**. For example, 20 mW of power delivered to the heater **803** can achieve a targeted 5 K of laser temperature steering. Also, a steering efficiency of 0.25 K/mW can be achieved using the laser heating apparatus shown in FIG. **8**.

Although various embodiments described herein specify a particular spacing between a heater and a laser of a laser heating apparatus, other spacings can be implemented. For example, the spacing between the heater **603** and the laser stripe **602***a* in the embodiment of FIG. **6** can range from about 2 to 25 μm (e.g., 3-20 μm, 4-15 μm, 5-10 μm). By way of further example, the spacing between the heater **703** and the laser stripe **702***a* in the embodiment of FIG. **7** can range from about 30 to 70 μm (e.g., from 35-65 μm or 45-55 μm). Other spacings between a heater and a laser of a laser heating apparatus are contemplated (e.g., any spacing or spacing range from about 2 μm to about 120 μm).

FIG. **15** is a flow chart showing processes for heating a laser of a heat assisted magnetic recording slider in accordance with various embodiments. The method illustrated in FIG. **15** involves moving **1502** a slider relative to a magnetic recording medium, the slider configured for heat assisted magnetic recording and comprising a submount to which a laser unit is affixed. The method involves operating **1504** a laser of the laser unit in a non-lasing state and a lasing state. The method also involves controlling **1506** a heater embedded in the laser unit or the submount to generate preheat for heating the laser during the non-lasing state and to generate steering heat for heating the laser during the lasing state. In some embodiments, the method further involves controlling **1508** the heater to cause the heater to generate the preheat and the steering heat to avoid a temperature associated with power instability of the laser when in the lasing state during a write operation.

FIG. **16** is a schematic view of a representative HAMR apparatus **1600** and related components that can utilize heating of a laser to reduce laser output power instability (e.g., mode hopping) according to various embodiments. The example embodiment shown in FIG. **16** has a laser-on-slider (LOS) configuration. In FIG. **16**, the apparatus **1600** includes a slider body **1601** having a first surface **1604** and an air bearing surface **1605**. A submount **1602** is affixed on the first surface **1604** of the slider body **1601**. A laser unit **1603** is affixed to the submount **1602** and includes a heater **1607** and a laser **1609**. The heater **1607** and laser **1609** can be positioned relative to one another and have a spacing therebetween as previously described. The laser **1609** is situated proximate to a HAMR read/write element **1606**, which has one edge on the air bearing surface **1605** of the slider body **1601**. The air bearing surface **1605** faces and is held proximate to a moving magnetic recording medium **1611** during device operation.

While here the read/write element **1606** is shown as a single unit, this type of device may have a physically and electrically separate read element (e.g., magnetoresistive stack) and write element (e.g., a write coil and pole) that are located in the same general region of the slider body **1601**. The separate read and write portion of the read/write element **1606** may be separately controlled (e.g., having different signal lines, different head-to-media spacing control elements, etc.), although they may share some common elements (e.g., common signal return path). It is understood that the concepts described herein relative to the read/write element **1606** may be applicable to individual read or write portions thereof, and may be also applicable where multiple ones of the read/write portions are used (e.g., two or more read elements, two or more write elements, etc.).

The laser **1609** provides electromagnetic energy to heat the media surface at a point near to the read/write element **1606**. Optical path components, such as a waveguide **1610**, can be formed integrally within the slider body **1601** to deliver light from the laser **1609** to the recording medium **1611**. In particular, a local waveguide and NFT **1612** may be located proximate the read/write element **1606** to provide local heating of the media during write operations. The NFT **1612** is designed to support local surface-plasmons at a designed light wavelength. At resonance, high electric field surrounds the NFT **1612** due to the collective oscillation of electrons in the metal. Part of the field is directed into the recording medium **1611** and gets absorbed, raising the temperature of the recording medium **1611** locally for recording.

In FIG. **16**, the laser unit **1603** includes a heater **1607** comprising one or more heating elements configured to warm the laser **1609** in a manner previously described. In FIG. **16**, a processor (e.g., an analyzer) **1622** is illustrated communicating with a controller **1618**. The processor **1622** can be configured to determine a temperature of the laser, such as by use of a thermal sensor (e.g., sensor **201** shown in FIG. **2**) proximate or integral to the laser unit **1603**. Additionally, the processor **1622** can determine laser output power (e.g., from a photodiode), and compare laser temperature and an injection current supplied during the lasing state to stored combinations of laser temperature and injection current to determine a likelihood of mode hopping occurring for the laser during the lasing state. The controller **1618** can communicate with the processor **1622** and can be configured to vary the current supplied to the heater **1607** for varying a temperature of the laser to reduce the likelihood of mode hopping occurring during the lasing state.

The controller **1618** shown in FIG. **16** includes a heater control **1616** coupled to the heater **1607** and a laser control **1621** coupled to the laser **1609**. The controller **1618** communicates with the laser control **1621** to control lasing of the laser **1609** and communicates with the heater control **1616** to control when the heater **1607** is turned on and off relative to the non-lasing state and the lasing state. Typically, the controller **1618** can be used to control an amount of injection current supplied to the laser **1609** and an amount of current supplied to the heater **1607** to vary the laser temperature in a manner previously described.

The controller **1618** can include a write control module **1620** that controls various aspects of the device during write operations. For a HAMR device, writing involves activating the laser **1609** while writing to the recording medium **1611**. The laser control **1621** includes circuitry that switches the laser **1609** on and off, e.g., in response to commands from write control module **1620**. The heater control **1616** can activate the heater **1607** during at least a portion of the non-lasing state and at least a portion of the lasing state to warm the laser **1609** in a manner previously discussed.

Systems, devices or methods disclosed herein may include one or more of the features structures, methods, or combination thereof described herein. For example, a device or method may be implemented to include one or more of the features and/or processes above. It is intended that such device or method need not include all of the features and/or processes described herein, but may be implemented to include selected features and/or processes that provide useful structures and/or functionality. Various modifications and additions can be made to the disclosed embodiments discussed above. Accordingly, the scope of the present disclosure should not be limited by the particular embodiments described above, but should be defined only by the claims set forth below and equivalents thereof.

What is claimed is:

1. An apparatus, comprising:
a slider configured to facilitate heat assisted magnetic recording, the slider comprising;
an optical waveguide communicatively coupled to a laser and a near-field transducer, and a heater at or proximate the laser, wherein the waveguide, laser, near-field transducer, and heater are disposed on a common wafer substrate; and
the heater configured to generate preheat for heating the laser during the non-lasing state and generate steering heat for heating the laser during the lasing state.

2. The apparatus of claim **1**, wherein the heater is configured to generate the preheat and the steering heat to avoid a temperature associated with power instability of the laser when in the lasing state during a write operation.

3. The apparatus of claim **1**, wherein the heater is separated from the laser by a spacing ranging from about 2 μm to about 120 μm.

4. The apparatus of claim **1**, wherein the heater is separated from the laser by a spacing ranging from about 2 μm to about 25 μm.

5. The apparatus of claim **1**, wherein the heater is separated from the laser by a spacing ranging from about 30 μm to about 70 μm.

6. The apparatus of claim **1**, wherein the heater is separated from the laser by a spacing ranging from about 40 μm to about 120 μm.

7. The apparatus of claim **1**, wherein the heater comprises a resistive wire.

8. The apparatus of claim **1**, wherein the heater is located in abutment with the laser.

9. The apparatus of claim **1**, wherein the heater is located on the laser.

10. The apparatus of claim **1**, wherein the heater is located in the laser.

11. The apparatus of claim **1**, wherein the laser comprises a laser diode, an optically pumped semiconductor laser or a quantum well laser.

12. An apparatus, comprising:
a slider configured to facilitate heat assisted magnetic recording, the slider comprising;
an optical waveguide communicatively coupled to a laser and a near-field transducer, and a heater at or proximate the laser, wherein the waveguide, laser, near-field transducer, and heater are disposed on a common wafer substrate; and
control circuitry coupled the laser and the heater, the control circuitry configured to cause the heater to generate preheat for heating the laser during a non-lasing state and cause the heater to generate steering heat for heating the laser during a lasing state.

13. The apparatus of claim **12**, wherein the heater is configured to generate the preheat and the steering heat to avoid a temperature associated with power instability of the laser when in the lasing state during a write operation.

14. The apparatus of claim **12**, wherein the heater comprises a resistive wire.

15. The apparatus of claim **12**, wherein the heater is located in abutment with the laser.

16. The apparatus of claim **12**, wherein the heater is located on the laser.

17. The apparatus of claim **12**, wherein the heater is located in the laser.

18. The apparatus of claim **12**, wherein the laser comprises a laser diode, an optically pumped semiconductor laser or a quantum well laser.

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